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All communications should be addressed to the Editor.

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Notices of the Royal Aëronautical Society.

Applied Scientific Research.

On another page will be found a memorandum directed towards the safeguarding of applied scientific research in aeronautics which was drawn up by the Council and laid before the Secretary of State for Air (Captain the Honourable F. E. Guest, M.P.) at an interview on January 17th by a deputation consisting of the Chairman (Lieut.-Col. Mervyn O'Gorman), Prof. L. Bairstow, Sir Mackenzie Chalmers, Prof. B. Melville Jones, Colonel Alec Ogilvie and the Secretary.

Lectures.

Dr. Pullin's lecture having been postponed from February 2nd to March 16th, the next meeting will take place on Thursday, February 16th, at 5.30 p.m., at the Royal Society of Arts, John Street, Adelphi, when Squadron-Leader C. F. Portal will read a paper on "Methods of Instruction in Aeroplane Flying."

Air Conference.

The following members have been nominated to represent the Society at the Air Conference to be held in the Guildhall, London, on Monday and Tuesday, February 6th and 7th:—Dr. L. Bairstow, Wing-Commander Cave-Browne-Cave, H. Glauert, Major F. M. Green, Capt. G. de Havilland, Squadron-Leader R. M. Hill, Prof. B. Melvill Jones, Major D. H. Kennedy, Major A. R. Low, Lieut.-Col. W. Lockwood Marsh, A. Ogilvie, Lieut.-Col. M. O'Gorman, Dr. A. J. Sutton Pippard, A. V. Roe, Sir R. M. Ruck, Major G. H. Scott, R. V. Southwell, H. L. Stevens, H. T. Tizard, Major H. E. Wimperis, R. McKinnon Wood.

R.38 Memorial Research Fund.

The Council have appointed a Committee, consisting of Professor L. Bairstow, Wing-Commander T. R. Cave-Browne-Cave, Major R. V. Southwell and Major H. E. Wimperis, to consider the administration of the R.38 Memorial Research Fund. The following further donations to this fund have been received since the

publication of the last list in the December issue of last year, bringing the total up to and for 23rd January, 1922, to £1,202 17s. 10d. :—

	£	s.	d.
12th Squadron, Royal Air Force	43	7	3
V. Stefanson, Esq.	10	0	0
Griffith Brewer, Esq.	10	0	0
2nd Squadron, Royal Air Force, Fermoy	9	0	0
47th Squadron, Royal Air Force, Helwan, Egypt ...	7	11	7
Sir Mortimer Singer	5	0	0
70th Squadron, Royal Air Force, Heliopolis	4	17	0
Squadron-Leader D. Harries	2	2	0
Mrs. N. G. H. Hodgson	2	2	0
G. Reid, Esq.	2	2	0
S. Payne, Esq.	2	2	0
A. E. L. Chorlton, Esq.	2	2	0
Inspector-General W. Gwatkin, Canadian Air Force ...	2	2	0
Mrs. K. Reed	2	0	0
Major C. F. Abell	1	1	0
Colonel Ivan Dawson	1	1	0
Flying Officer J. S. G. Wrathall	1	10	0
Flight Lieut. H. C. Irwin	1	1	0
A. E. Marsland, Esq.	0	10	6
Total	£109	11	4

Examinations.

It would greatly assist the Council in making the necessary arrangements if intending candidates for the Society's Associate Fellowship examinations, to be held in April next, would send in their names provisionally as early as possible.

Foreign Publications.

By arrangement with the publishers, arrangements have been made for copies of the French publications " L'Air " (1s. 3d. post free), " La Technique Aéronautique " (6½d. post free) and " L'Indicateur Aérien," to be obtainable by members at the Society's offices.

Arrangements for the Month.

Feb.	1, 2.0 p.m.	Candidates' Committee.
	2.30 p.m.	Special Meeting of Council.
,,	7 and 8.	Air Conference at the Guildhall.
,,	16, 5.30 p.m.	" Methods of Instruction in Aeroplane Flying," by Sqdr.-Ldr. C. F. Portal, at the Royal Society of Arts.
,,	21, 4.0 p.m.	Library and Publications Committee Meeting.
	4.30 p.m.	Candidates' Committee.
	5.0 p.m.	Council.

W. Lockwood Marsh, *Secretary.*

THE IMPORTANCE OF RESEARCH IN AERONAUTICS.

The following is an epitome of the views of the Council of the Royal Aeronautical Society on the need for better safeguards to prevent the submerging of applied scientific research in aeronautics by technical *ad hoc* experimental work. These views were laid before the Secretary of State for Air at a recent interview by a deputation of the Council consisting of Colonel M. O'Gorman, C.B., D.Sc. (Chairman), Professor L. Bairstow, C.B.E., F.R.S., Sir Mackenzie Chalmers, K.C.B., C.S.I., Professor B. Melvill Jones, A.F.C., and Lieutenant-Colonel A. Ogilvie, C.B.E. :—

The Royal Aeronautical Society's Council asks to be allowed to put before the Air Minister in person certain views which have been borne in them in relation to applied scientific research in aeronautics. They would lay before the Minister the standing of the Aeronautical Society and its quality to approach him on technical matters.

Four bodies represent British aeronautical activity, and these bodies respect each other's domains and are connected by agreements and joint committees—they are :—

(*a*) The Royal Aero Club, concerned with the control of races, competitions and touring, the international sporting and touring rules and triptyques.

(*b*) The Air League of the British Empire, concerned with propaganda, mainly in the interests of aerial defence.

(*c*) The Royal Aeronautical Society, whose province is the spread of the study of aeronautical technics, both in theory and practice, including those branches of physics, chemistry, etc., which relates to aeronautics—as well as scientific research and publications therewith. This Society is officially represented on the Aeronautical Research Committee of the Air Council.

(*d*) The Society of British Aircraft Constructors, the organised body of British constructional firms. The technical staff of the last are, in significant numbers, members of the Royal Aeronautical Society.

Applied scientific research has in England for one reason or another suffered from serious and increasing disabilities since the earliest flight. These disabilities arose from many causes, but notably from the fact that though research has forced itself into public recognition as fundamental to any technical advancement, when it comes to the detailed allocation of time and work this recognition becomes blurred by reason of other factors, technical, administrative, and financial, which tend to obscure its fundamental importance and crowd it out of existence. The occasional and (we venture to suggest) incorrect usage of the term " research " as a comprehensive name for all and any experimentation in aeronautical technics has led to its use to cover matters other than the true " applied scientific research " to which it is the object of the Royal Aeronautical Society to draw the Minister's attention.

" Aeronautical technics " (or research so-called) embraces many sub-heads, thus not only—

(1) Applied scientific research (properly so-called) whether theoretical, model or full-scale work, and referred to hereafter for brevity as Research,

But also

(2) *Ad hoc* experimentation and calculation on specific appliances, or proposals not forming part of an organised series.

(3) Experimentation to develop acceptable devices into standard useful appliances.

(4) The improvement of such devices in accordance with the demands arising from use and the introduction of modification specified for service reasons.

(5) Tests of performances of normal purchases for service.

(6) Etc.

This list may be extended . . . the above sub-heads are intended to be illustrative and not inclusive.

In a number of cases there is no confusion between what falls under one or another of these sub-heads; but there are limiting cases, when a form of words intended to lay down what is and what is not applied scientific research would lead to discriminating wrongly between research and other sub-heads.

The desire of the Royal Aeronautical Society is to ensure, if possible, the continued and urgent prosecution of Research as above defined. This is the Society's main plea.

As regards *method,* the Society hopes to give point to the above request by certain suggestions for the consideration of the Air Minister.

If the question of an organisation to deal with the matter be now considered we find that on the one hand all the heterogeneous activities above enumerated as aeronautical technics, which often have little in common except the fact that they are susceptible of being called "technical," might be ascribed, as and when they arise, to the same chiefs, the same sub-section of the money vote, dealt with by the same staff, and in the same establishment; or on the other hand, if one of them appeared to be of basic importance it might be specifically protected from encroachments.

These encroachments are natural, are known to occur in technical organisations having this diversity of interests and are easily explained, none the less they are difficult to guard against. They have been observed both in this country and abroad where for any reason *ad hoc* experimentation and applied research are in juxtaposition—which implies competition for the use of the time and services of the same staff. Thus, each *ad hoc* experiment which presents itself as desirable, and such always looks desirable or it would not be touched, (for example, the verification of some particular wing shape or wing thickness, put forward by an enthusiast or maker as having exceptional merits) appears to call for prompt attention; it seems to offer a royal road to results; the experiment would appear to be one of which the end can be foreseen and the amount of expenditure estimated; while the answer which the experiment affords will apparently be either positive or negative, but in either case useful.

In contrast, Research (for example, the investigation of aircraft control at low speeds, of pressure distribution on wings, of the twist and vibration of airscrew blades in flight, or the control of aircraft from the ground at night or in fog) is rarely backed by the pressure of an enthusiast who vaunts the advantages of his specific device, nor is it clear how long such an investigation will have to be prosecuted; still less what important side issues will have to be explored before its harvest of results can be expressed in terms of actual aircraft.

The administrative head thus finds himself confronted on the one hand (A) by a number of requests for research, of which he cannot foresee either the exact end, the total cost or the exact resulting advantage, and (B) with demands for the verification of the alluring claims of some particular device; while, and in addition to the above conflicting demands for technical attention, there are (C) the service demands for introducing improvements in existing, and standardisation of proposed, technical appliances, and other kindred matters. The plea of the Council of the R.Ae.S. is that, particularly in a time such as the present of

reduced expenditure, the position of Research as above defined shall be *specifically* safeguarded in some manner. Throughout the war it was openly urged that *ad hoc* experiments must take precedence of research, and there is no doubt but that they did so—an attitude with which the Royal Aeronautical Society is in full harmony. Prior to the war much the same result was to be observed, for reasons which need not be entered upon at the present time. In the post-war period analogous troubles are liable to arise. The Royal Aeronautical Society urges upon the Air Minister that research is the fertiliser at the root of the tree of progress; without it the tree will not only fail to grow, it will die and all that will then be available is the standing wood.

The constructive suggestion which this Society puts forward to give point and practicability to its proposal for the safeguarding of Research in aeronautics, which is its main theme, is that a precedent found in the organisation of the Admiralty be followed in its general outline by the appointment of an individual of high scientific qualifications whose specific duty will be the safeguarding of Research, keeping it in touch with the scientific work of the country, and with the problems of civil and military aircraft. Those characteristics of the office in question, to which we wish to draw attention, are as follow :—

(1) That a grant of money be specifically allotted to research, as above defined.

(2) That the individual holding this office shall have access to the Members of the Air Council.

(3) That he have access to private advice, and have money specifically available to him for the purpose of paying for such advice.

(4) That there be an Advisory Committee external to the Air Ministry, consisting of scientific men. This Committee to have no executive powers and be solely advisory.

(5) That this Committee should supervise and publish such matters relating to research as are deemed to be publishable in the public interest.

In addition to the above, the Council of the Royal Aeronautical Society trust that support will be continued to the movement for giving scientific training to selected officers of the Royal Air Force, so that highly-experienced pilots shall be able to suggest and intelligently take part in Research work—to which such assistance will be invaluable.

In conclusion, the Royal Aeronautical Society points out that any retrenchments of administrative staff or expenditure in construction form strong reasons for safeguarding that least expensive and most fruitful form of activity—Research.

It is, finally, desired to make it clear that the Service members of the Council have felt that their Service appointments debar them from expressing any opinion on this matter.

PROCEEDINGS.

FIFTH MEETING, 57th SESSION.

An Ordinary General Meeting was held in the Rooms of the Royal Society of Arts on Thursday, December 15th. Lieut.-Colonel O'Gorman, Chairman, was in the chair.

The CHAIRMAN, in opening the meeting, said that the Lecturer that evening was Major F. M. Green, with whose technical and scientific work they were all probably familiar. Any lecture from an engineer of his experience in his subject would well repay attention.

Major GREEN said that before giving the paper he wished to make one personal remark in which he would, perhaps, be anticipating criticism, and that was to say that he was not a pilot. His flying experience was limited to a very few very short flights on an old machine. He was certainly not a fighting pilot, and therefore he wished them to understand that the paper had been written from the designer's point of view, although he had tried to collect opinions from all the fighting pilots that it had been his privilege to meet. Perhaps on this occasion he would hide behind the proverb "Onlookers see most of the game."

Major F. M. Green, O.B.E., M.I.C.E., F.R.Aë.S., etc., then delivered the following lecture:—

DEVELOPMENT OF THE FIGHTING AEROPLANE.

There was perhaps nothing in aeronautics that developed so quickly during the Great War as the fighting aeroplane. At the beginning of the war the use of offensive weapons on aeroplanes was almost unknown. The idea of fighting in the air had hardly been discussed and certainly no country had made provision for carrying offensive weapons as part of the regular equipment of the aeroplane. Long before the end of the war every aeroplane was armed to a greater or lesser extent, while particular types of aeroplanes had been developed whose chief duty was the destruction of enemy aircraft and the protection of aeroplanes of its own country which were engaged in various specialised duties, such as reconnaissance and bombing.

In the truest sense of the word all aeroplanes used in warfare are fighting aeroplanes, but the scope of this paper is limited to those machines which are used primarily as weapons of offence against opposing aircraft.

Historical.

When the first aeroplanes were made, the actual flying was found of sufficient difficulty to make the thought of carrying out any special duties remote. As the knowledge of aeronautics increased, it began to occur to designers that the uses to which the aeroplane would be put in war might influence the design. At first it was thought that if one passenger were carried and a fairly good view of the ground were obtained, then the rest of the designer's energy could be devoted to improving the safety, reliability and speed of the aeroplane. It was this stage of development that had been reached when war broke out. The only offensive weapon that had been proposed was a carbine carried by the observer in a two-seated aeroplane.

The idea of an aeroplane solely for offensive purposes had not been seriously considered. Single-seated aeroplanes of fairly high speed had been made and in

England they were generally called Scouts. The general idea was that such aeroplanes should obtain information as quickly as possible, and I do not think that the idea of using them offensively to attack opposing aircraft was in any case the basis for their design. The most notable examples of these types of aeroplane in this country were the Bristol Scout, the Sopwith Tabloid, and the series of aeroplane with the prefix S.E., designed and made at the Royal Aircraft Factory as it was then called. The first of these machines was produced at Farnborough and first flew about the spring of 1911. It was known as the S.E.1 and attained a mean speed of 90 miles an hour flying near the ground over a short course. Various developments of these aeroplanes were made in the time preceding the war, and in the early summer of 1914 an aeroplane, which was to all intents and purposes purely a racer, was tested at Farnborough. It is interesting to note that this machine was fitted with flaps the complete length of the wings, so arranged that the angle could be altered during flight in order to decrease the landing speed. It was intended that this machine should go overseas with the expeditionary force, but it was damaged in a trial flight and it was not considered worth while repairing it. It must be remembered that none of the machines hitherto mentioned were fitted with guns of any sort and as weapons of offence they were of no value.

The aeroplanes that accompanied the British Expeditionary Force were almost entirely of the B.E. and Maurice Farman type, both of which are so well known as to require no description. It very soon became apparent that fighting in the air would become a serious business, and all sorts of gun mounts were devised which were to carry the Lewis gun. On the B.E.2 aeroplane it was usual to fit no less than five different mounts on which the gun could be supported, so as to make it possible to defend the aeroplane from as many points of attack as possible. In this aeroplane the observer sat in front of the pilot and this considerably increased the difficulty in obtaining good shooting.

At the beginning of the war firing through the propeller was unknown, and therefore on a tractor aeroplane the airscrews blocked out a large amount of useful field of fire. In order to get over this difficulty it was decided to develop a pusher aeroplane so that the gunner could have an unrestricted field of fire forwards. Three service aeroplanes were produced, two at the R.A.F. and the other designed by Captain De Havilland at the Aircraft Mfg. Co. The F.E.2 type was a two-seater aeroplane and the D.H.2 and the F.E.8 were single-seater fighters, made solely for offensive purposes. It was originally intended to make full use of the field of fire by providing a gun mount which enabled the pilot to fire in all directions forwards. It was found to be of little use on the single-seaters on account of the difficulty of manœuvring the aeroplane and the gun at the same time, and eventually a gun mounting was used which allowed for elevation only. Both types of the single-seater pusher were successful for a time and the F.E.2 had a long period of usefulness, though the later part of it was used more for general utility work than for offensive fighting.

Soon after the war started the usefulness of the speed of tractor aeroplanes became apparent, and the need for firing straight ahead became urgent. The first method used was to fix hardened steel deflector plates on the propeller blades so that the bullets which did not pass between the blades were deflected without damaging the airscrew. This worked fairly well, but added considerably to the weight of the propeller. It was soon superseded by a synchronising device which timed the bullets to pass between the blades. Various gears were used, some mechanical, others hydraulic, the latter type being adopted by the British Air Service. The result of the use of these devices was to establish the tractor aeroplane as the most useful offensive fighting machine and the small pusher type was altogether superseded. Although this policy was no doubt correct with the conditions as they were, it is by no means certain that the future development of small fighting aeroplanes will be solely of similar type.

Towards the latter part of the war the usefulness of two-seater aeroplanes for offensive work became apparent. If it were possible to develop training to a sufficient degree to get a real understanding between the pilot and the gunner, then there is little doubt that this type of aeroplane might compete very seriously as an offensive fighter with the single-seater. It must not be forgotten, however, that an aeroplane that carries one man is more economical than one which carries two men, and that the two-seater fighter must prove itself definitely more effective than the single-seater before its use for offensive purposes can be considered.

A number of single-seater tractor aeroplanes were made, generally of the biplane type, while both monoplane and triplane were used to some extent. The size of aeroplanes gradually went up until the standard single-seater machines weighed 1,700 to 2,000lbs. fully equipped, with horse-powers from 150 to 200. Since the end of the war aeroplanes with still higher performance have been developed weighing about 2,100lbs. and equipped with 300 h.p. engines.

This historical survey is very brief and has been mentioned more with the idea of suggesting future developments than with the intention of putting on record the history of the fighting aeroplane during the Great War.

In considering the future development of fighting aircraft we must bear in mind that there are a number of different kinds of war and that the requirements of each kind are separate and distinct. It obviously is no use having aircraft specially designed and equipped for fighting enemy aircraft if the enemy have no aircraft to fight. Highly developed single-seater aeroplanes, therefore, are no use whatsoever in savage warfare. Again, the performance required of the fighter aeroplane depends chiefly upon the performance of the aeroplanes to which it is in opposition. If the enemy aircraft are not first rate then it is more economical to use a slightly slower fighter of more general utility than to use the fastest and most fined down machine that can be produced.

The single-seater fighters, therefore, will only become of great importance for first-class wars, and it is essential that their design shall always be at least as advanced as the aeroplanes of the enemy. It will always be possible to make a small machine carrying little load that is faster and more manœuvrable than aeroplanes designed for heavier duties, for whatever improvements may be made in aeronautics are likely to affect the one type as much as the other. The safest way to ensure development, therefore, is to aim at a performance which is appreciably better than the best aeroplane of a larger type that the designer himself could make. It is not possible to know exactly what other people are doing, but we can feel fairly certain that if a designer is capable of designing a good fighting aeroplane at all, he will also be capable of knowing what the best performance is likely to be on a larger machine.

Armament.

As the duty of the fighting aeroplane is to fight, the starting point for design should certainly be the armament, that is to say, the position and number of the machine guns or other weapons carried and the suitability of the aeroplane to enable the pilot to bring those guns into such a position that they can most effectively be used. Assuming for the moment that machine guns of the type used in the late war remain unchanged to any serious extent, then we have to decide the best number of machine guns to be carried, the amount of ammunition that should be taken and whether or not the guns should be fixed to fire straight ahead or whether we should attempt a bigger field of fire.

In air fighting the amount of time that the fighting aeroplane is in a favourable position to shoot at its opponents is likely to be very limited, and as accuracy of fire will probably never be great, it is essential to provide means for firing the greatest number of bullets during the favourable periods, or in other words, to have as many guns as possible which fire as rapidly as possible. On the other

hand, the length of time that the aeroplane will be favourably situated for firing at its opponent depends upon the relative performance and manœuvrability of the two aeroplanes. Adding more machine guns and carrying more ammunition will increase the size of the aeroplane, and will reduce both its performance and its manœuvrability. As in all other matters of engineering design, therefore, we have to effect a compromise. There can be no rule for predicting what this compromise will be in the aeroplane yet to be designed. All we can say is, that at the end of the last war the equipment consisted of two machine guns each firing at the rate of 1,000 rounds per minute and that the ammunition carried was about 1,200 rounds. In a more recent design it has been found possible to increase the ammunition to rather over 2,000 rounds. From the above considerations it can be safely said that anything which will increase the rate of fire in an aeroplane without increasing the weight will be a distinct advantage, and the writer thinks that this is one point in which we may look for improvement in the fighting power of future machines. It is convenient to use equipment similar to that which has been developed for land warfare, but at the same time it seems probable that the fighting power of our aircraft could be very much improved if a special gun were designed consisting of two, three, or more barrels in which the rate of fire was increased to perhaps twice that of the present equipment.

Hitherto we have only considered guns of the machine gun type. It is possible that advantage will be found in firing a bullet larger than those of the present calibre. It is also possible that guns will be produced firing something more of the nature of shrapnel. The writer prefers not to suggest development along these lines, but will content himself by remarking that whatever is produced must be small and light, otherwise the all-important power of dodging will be lost.

View.

Having now decided that we must get a maximum rate of fire consistent with other factors, the next point to which we must give attention is to enable the pilot to place his aeroplane in a position favourable for using his guns. The chief points to be studied to enable this to be done are the view that can be obtained from the aeroplane, the speed of the aeroplane, its rate of climb and ceiling and the manœuvrability of the machine.

The question of view is of an importance that can scarcely be exaggerated. The fighting pilot not only has to seek out the enemy aircraft, but must also be able to avoid being attacked unawares. His ideal field of view would of course have no obstructions at all, and this is obviously impossible. It is important that such obstructions as are unavoidable shall inconvenience him as little as possible. Experience has shown that it is almost essential that his view of the complete upper hemisphere should be unobstructed; that he shall be able to see down vertically over the side of the machine, and ahead and downwards to as big an angle from the horizon as he is able to get. Various positions have been tried on tractor scouts. It is the writer's opinion that by far the best compromise is obtained when the pilot sits with his head in line with the chord of the top plane and not too close to it. The front of the fuselage should slope down towards the engine and the lower plane should be of as narrow chord as possible and have its trailing edge about vertically beneath the pilot. By this means the view in the upper hemisphere is unrestricted and the lower plane offers comparatively little obstruction (Fig. 1). In any case it is easy to dive the machine sharply for a moment in order to make sure that nothing is being hidden by the lower plane. It is obvious that a still better view could be obtained by having no lower plane; in this case the aeroplane becomes a parasol monoplane. Unfortunately it is not easy to make an aeroplane of this type without certain compensating disadvantages, and in fact such an aeroplane has not up to the present been particularly successful. The disadvantage of a comparatively narrow lower plane is small, while the

advantages from other points of view seem to make it worth while keeping to the biplane type.

Triplanes have been made and the narrow chord is of some slight advantage for view, but the fact that it is necessary to have three planes makes it impossible to obtain a view which is as good as in the type just described.

In an aeroplane designed by Captain De Havilland, known as the D.H.5, the pilot was actually in front of the top plane, and was seated over the bottom plane to achieve this result. The trouble with this for good visibility is that the view of the upper hemisphere behind the pilot is seriously obstructed. It is also rather worse for aerodynamic reasons.

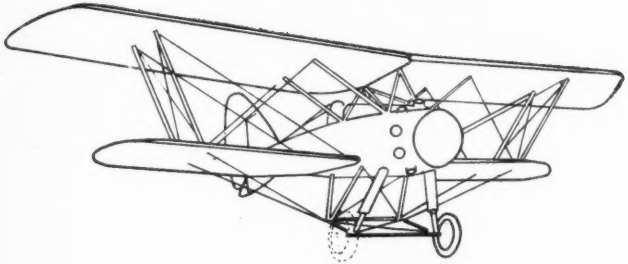
A third type of scout was also much used in which the pilot was placed as close to the engine as possible and was seated more or less underneath the top plane. For visibility this is not good, as the top plane obscures a large portion of the upper hemisphere. To avoid this a hole is sometimes cut in the plane, but this is only a partial cure and is bad for aerodynamic reasons. In certain cases the pilot's head is actually in a hole in the top plane. This certainly allows a good view of the upper hemisphere, but it is inclined to be awkward and is not popular with pilots, who seem to be afraid that if the aeroplane does turn over on the ground they will be in for a bad time.

The chief objection that is generally raised to seating the pilot behind the top plane is that the moment of inertia of the whole aeroplane is increased, and this makes it slow to manœuvre. For a long time it was claimed as one of the chief advantages of the rotary engine that it enabled the pilot to sit close up to the engine and produced an aeroplane which was extremely easy to manœuvre fore and aft. The writer thinks there are two fallacies in this view. Firstly, the increased gyroscopic effect of the rotary engine is equivalent to an increased moment of inertia of the aeroplane, and it can easily be shown that the decrease of moment of inertia is more than compensated by the gyroscopic moment. The other fallacy is that as it is always easily possible to manœuvre a small aeroplane fast enough in the fore and aft direction to break it, it is of no advantage to provide a quicker control than we have now without increasing the strength of the machine beyond what is practicable.

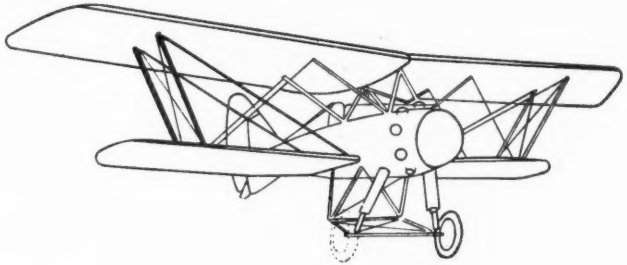
Ability to Withstand Damage.

The structure of the aeroplane itself is a large target in comparison with the pilot and the vital parts of the engine. It will be a big advantage if the aeroplane is so designed that it is likely to lose little of its structural strength when hit by the bullets of the enemy. Wooden spars are generally of such a section that many bullet holes are unlikely to cause sufficient damage to make failure in the air likely. There is always the possibility that a wire or the attachment of a wire will be shot away, and it certainly seems a requirement of the modern aeroplane that the structure of the aeroplane should not depend upon any single wire or attachment. Duplicating a wire by means of another wire alongside is apt to be dangerous as one bullet is likely to destroy both wires. The lecturer knows of one case in which an aeroplane partly collapsed when a bullet hit the point of attachment of two wires which left the plane at different angles. The ideal arrangement, therefore, is to make a structure which is braced by two or more independent systems.

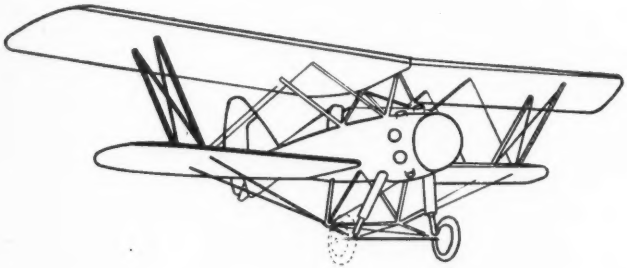
In the Siskin aeroplane, designed by the writer, the scheme of duplicated bracing has been carried out to a considerable degree of safety. It will be seen (Fig. 2) that the aeroplane is braced in the ordinary way by wires between the planes and that the wires are duplicated by the incidence bracing. In addition to the usual bracing there is a complete system of bracing to a king post under the body, which will give a fair factor of safety to the whole aeroplane if all the



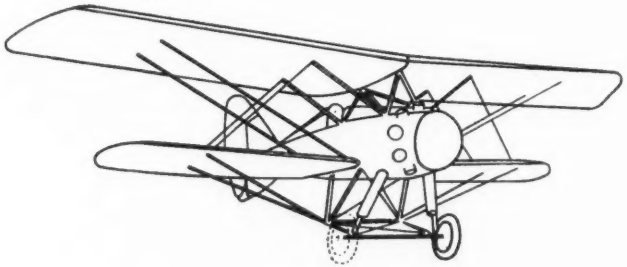
WING BRACING COMPLETE.



AUXILIARY BRACING SHOT AWAY.



MAIN LIFT WIRES SHOT AWAY.



STRUTS SHOT AWAY.

main bracing is shot away, so long as either the incidence bracing or the struts remain in place. We have in fact a structure in which the failure of any one wire increases the load on to two other wires. It seems reasonable to suppose that a structure of this type is very nearly safe from failure in the air from anything less than a direct hit by a shell.

As regards damage to the power plant, air-cooled engines certainly are at a big advantage in comparison with those which are water cooled. The danger of having the water system pierced is considerable, and although this does not immediately bring down the aeroplane, the loss of water will certainly mean a seized engine in a very short time.

Fire.

One of the greatest dangers to which a fighting pilot is subject is risk of being set on fire by an incendiary bullet. Towards the end of the war self-sealing tanks were introduced, which reduced this risk immensely. These, however, are rather difficult to make and add somewhat to the weight of the aeroplane. It seems possible that a similar effect might be obtained by surrounding the petrol tank with inert gas, as for instance cooled exhaust gas, and arranging to drain any accidental leakage of petrol overboard as effectively as possible. Unfortunately this would probably come out almost as heavy as the self-sealing tanks and would have the disadvantage that more petrol would be lost if the tank is hit.

Performance.

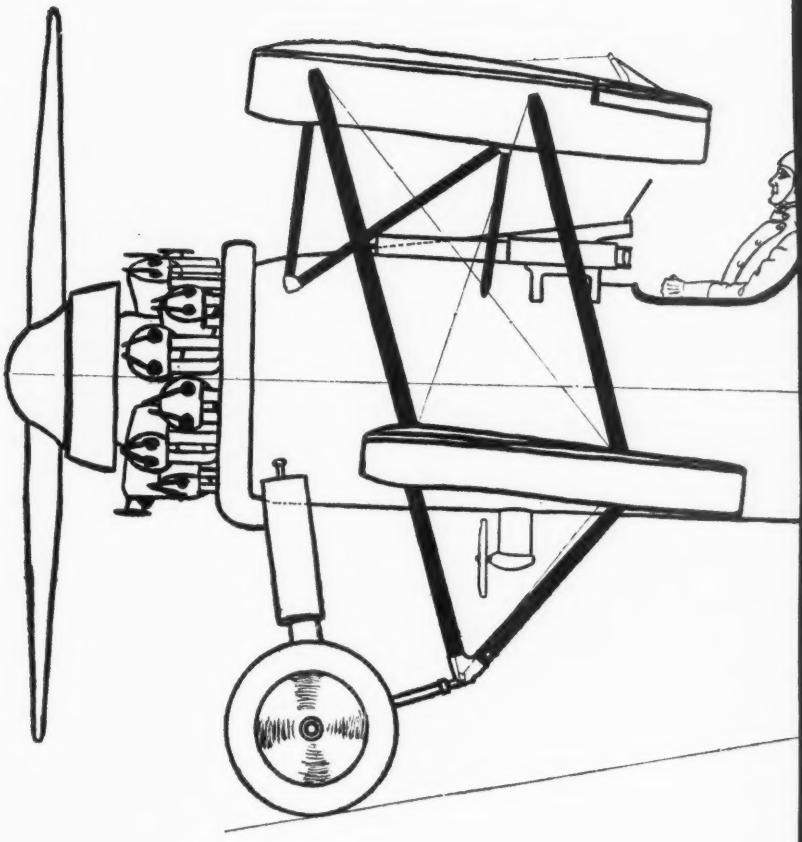
In order that a fighting pilot shall be able to choose the most favourable position when engaged in an aerial combat it is necessary that he shall always be able to outmanœuvre his opponent, and at first sight it might seem that speed is the chief requirement. Experience has shown that rate of climb is the governing factor; the aeroplane at the greater height can always obtain extra speed by diving, consequently the aim of the fighting pilot is generally to outclimb his opponent. In addition to this, the ability to climb is also to a large extent a measure of the ability to manœuvre rapidly at height, for it is necessary to have excess power to be able to turn quickly without losing altitude.

There are many ways by which ability to climb at high altitudes can be increased. The ratio of horse-power to weight can probably not be much increased as on certain aeroplanes this figure is no more than 7 lbs. per horse-power of the loaded aeroplane. Decreasing the wing loading in the general way increases rate of climb, but it has other disadvantages. The most promising way of increasing the ceiling and the rate of climb at high altitudes is to design engines which give the same or nearly the same horse-power at considerable heights as they do at ground level. This has already been done experimentally in this country and elsewhere. The most successful means up to the present is to provide a centrifugal type of air compressor which increases the density of the air supplied to the engine so as to keep it at ground level density. The extra weight of the gear is not very great and it is possible to maintain almost the full horse-power of the engine up to considerable altitudes. The same air compressor can be used to supply air at ground level density to the pilot, and thus the necessity for carrying oxygen can possibly be avoided.

By using air compressors there is really no reason why the ceiling of a Scout aeroplane should not be increased from rather over 20,000ft., as it is now, to 35,000ft. or 40,000ft. As it is probably too much to expect that pilots should fly at these great heights, the gear will be used rather to increase the rate of climb and manœuvring power of the aeroplane at altitudes of about 20,000ft.

Manœuvrability.

As we have seen in the last paragraph, manœuvrability is largely a matter of performance. At the same time all aeroplanes with similar performance have



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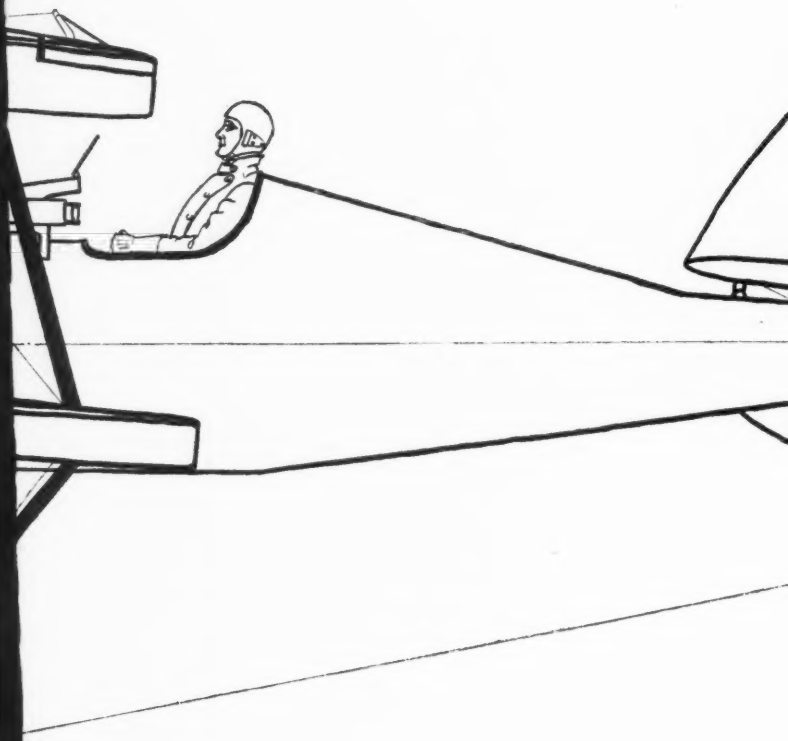
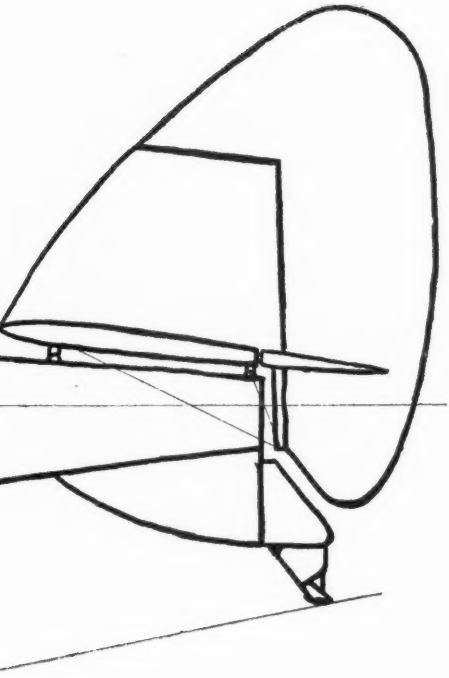
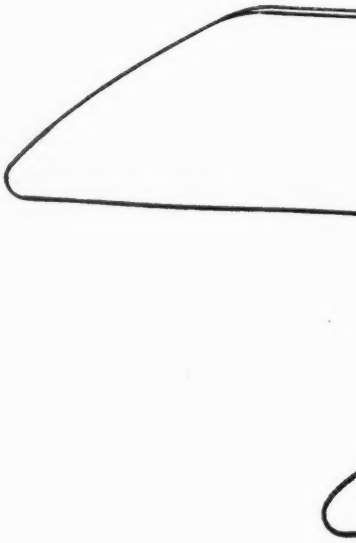


FIG. 1.





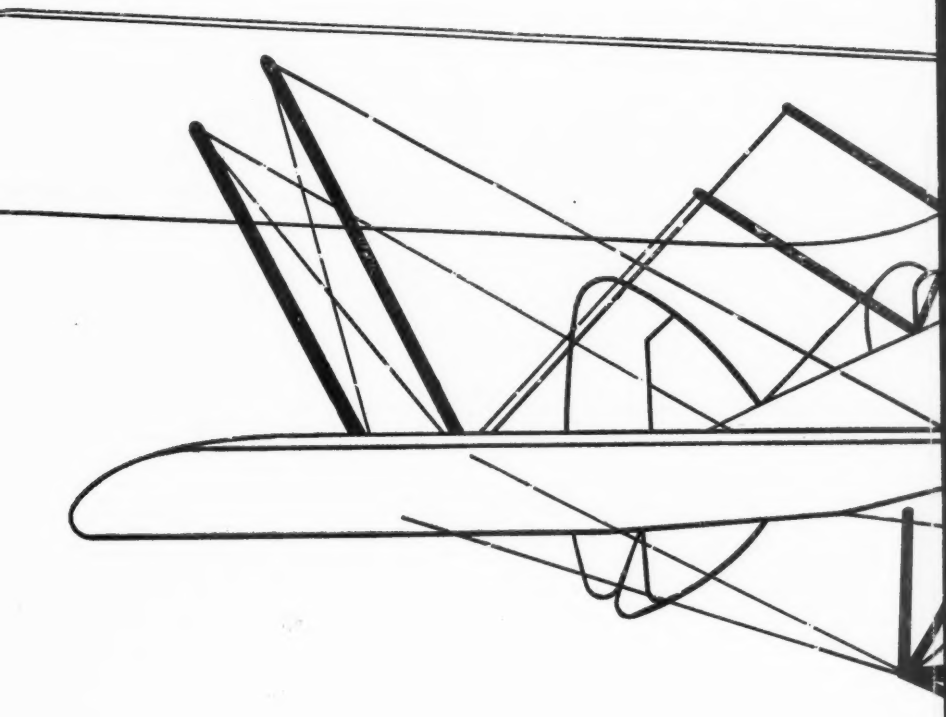


FIG. 2.

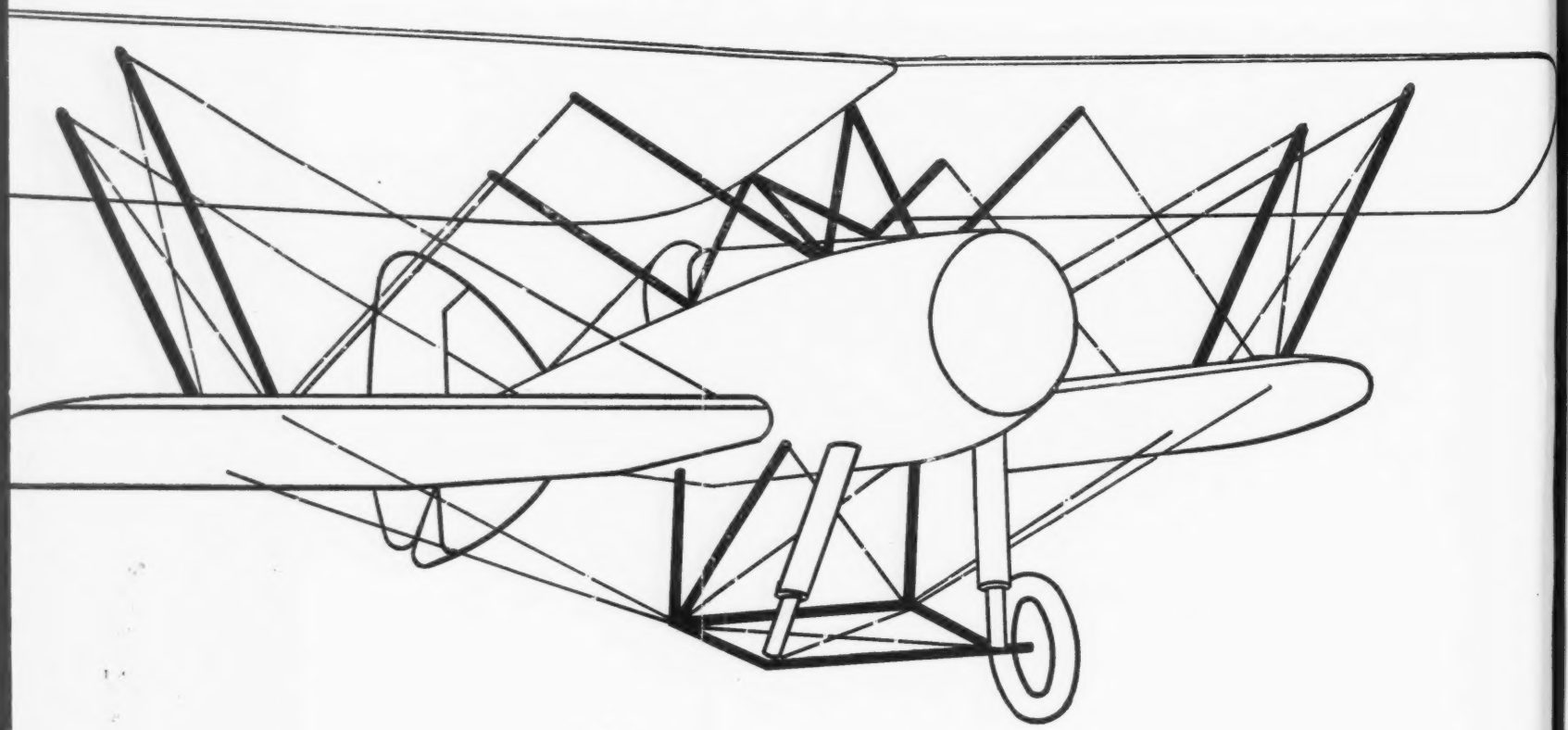
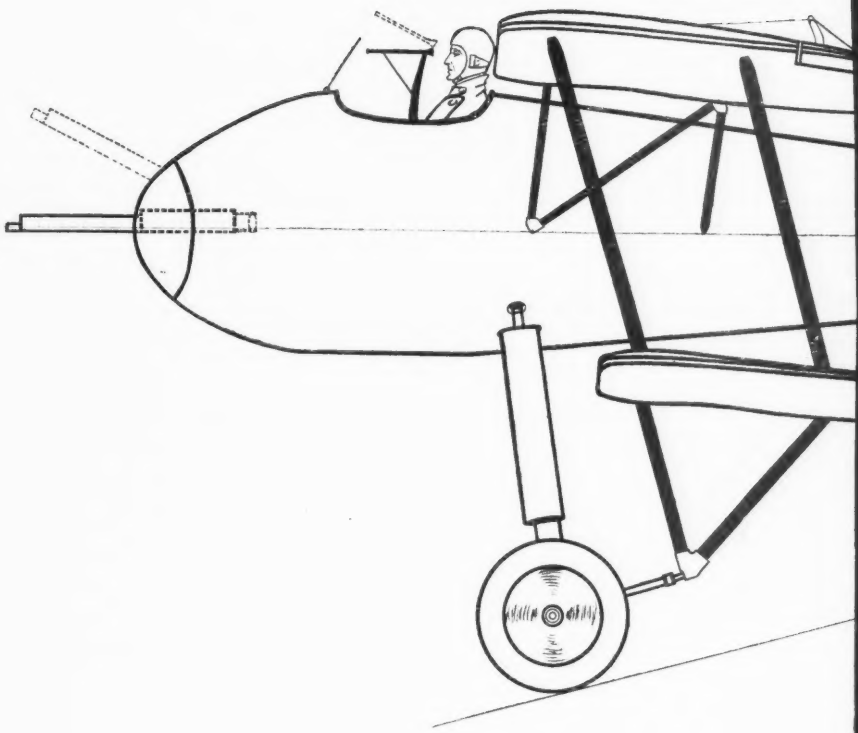


FIG. 2.



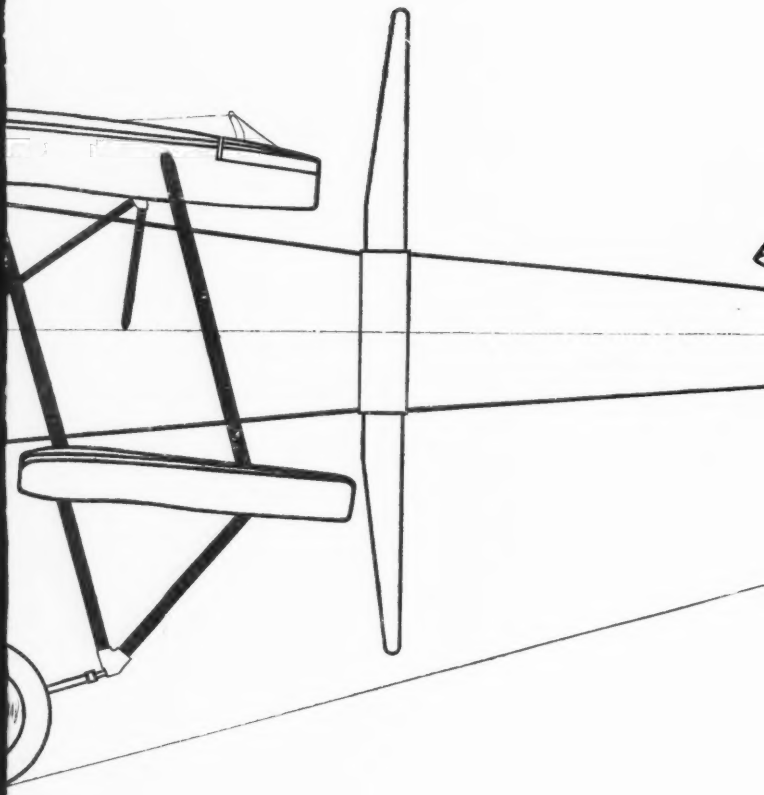
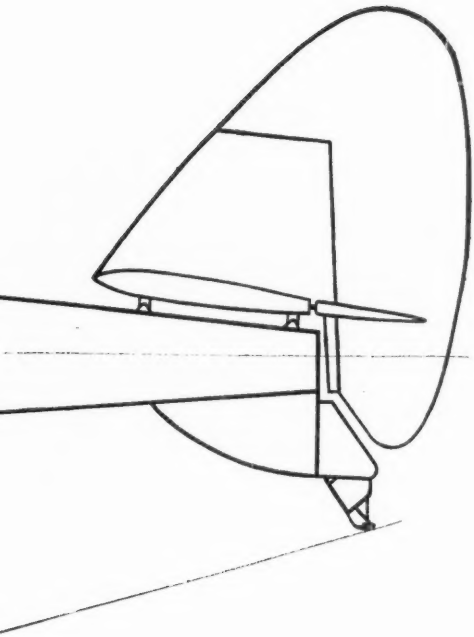


FIG. 3.



not equal power of manœuvring. It can easily be shown that the minimum circle in which an aeroplane can turn depends directly upon its stalling speed, hence the more lightly we load an aeroplane the more manœuvrable we may expect it to be. Unfortunately it is equally obvious that the more rapidly we manœuvre an aeroplane the stronger it needs to be; also the bigger the planes are, the heavier they will be. As usual, therefore, we have to arrive at a compromise which usually results in fighting Scouts being loaded from 7 lbs. to 9 lbs./sq. ft.

Experience of the late war has shown that there are two distinct and separate types of fighting. In the one the fighting pilot climbs to a height well above his intended victim and attacks in one long dive. If he misses he makes use of his superior speed and climbs to gain height and to repeat the manœuvre. The other type of fighting is that which takes place between aeroplanes which are very nearly equal in performance and frequently between large numbers of machines. In this case the aeroplanes manœuvre round one another at fairly close range, each endeavouring to get into a favourable position to fire at the other and to avoid being fired at in return. For this type of fighting the more lightly the aeroplane is loaded the better, while in the former type heavy loading is an advantage rather than otherwise. The heavier-loaded aeroplane will dive faster and probably be steadier on the dive, but it will be less able to turn quickly and fight well in what is generally called a "dog fight." During the latter part of the war fighting aeroplanes fell actually into two classes—those of the S.E.5 type, which were fairly heavily loaded, were used for the former type of fighting, and those of the Sopwith Camel type were chiefly used for the latter. Whether or not it is possible to combine both types of fighter in one aeroplane is open to question, but it certainly seems probable that an aeroplane designed to do for both classes of fighting will be less effective than one which is designed either for the one class of fighting or the other.

Two-Seater Fighters.

The case of the two-seater is much the same as the single-seater fighter, but the addition of the gunner makes it possible for the two-seater to fire in directions other than straight ahead. This to some extent makes up for the somewhat slower speed of manœuvre from which all two-seater aeroplanes are likely to suffer on account of their increased size. The value of the two-seater will depend almost entirely upon the degree to which training in gunnery can be developed. The question of aimed fire from an aeroplane is one of considerable difficulty, and the more rapidly the aeroplane is manœuvred the more difficult does it become.

Gunnery.

Although much experimental and research work was done towards improving the standard of aerial gunnery during the Great War, the conditions of training were such as to make it impossible to provide sufficient training to make the best of things. In the general way, the fixed gun firing straight ahead was as much as a pilot could manage, and comparatively few pilots became even passably expert. In special cases, as undoubtedly in that of the late Captain Ball, V.C., successful use was made of a Lewis Gun fixed to the top plane, mounted so that the elevation could be altered, but comparatively few other pilots copied the example of that highly successful air fighter.

It seems to the writer that further development of aerial gunnery depends entirely on the attitude taken up by the Air Force authorities, and to the time and energy they are prepared to put into the training of our future fighting pilots. If there is the demand, it is certainly possible to arrange for movable guns which can fire through the propeller, or to make fighting aeroplanes in which the propeller is behind the pilot. It is also possible to arrange that the effort of moving the

gun or guns can be provided mechanically, and that all the pilot has to do is to move the sight with the knowledge that the gun will turn with it. Mechanism of this type can be made, but it has little chance of being made unless the demand for it comes through the Royal Air Force itself.

It will probably be said that the suggestion of moving the gun and the aeroplane in different ways at the same time is hopelessly difficult and is scarcely worth attempting. The reply to this is that many other equally difficult things have seemed to be impossible, but gradual improvement in training has so developed the technique of it that what once appeared to be impossible now becomes comparatively easy. Some 200 years ago Sebastian Bach wrote certain music for the violin which nobody could play. Later on there arose some violinists of genius who managed to surmount the technical difficulties and to do what had been believed to be impossible. Gradually the technique of violin playing was developed until at the present day this same music can be played by boys and girls of comparatively tender age and it is no longer looked upon as a mark of anything more than good training to be able to do so. In the same way it is probable that we shall find one or two pilots at least who will be able to move the gun and aeroplane at one and the same time. Directly this has become possible, then a careful study of the technique should enable training to be devised so that any pilot of ordinary ability can be trained to do the same thing.

If the Royal Air Force decide that such skill is necessary, then there is no doubt that it can be obtained and the type of fighting aeroplane may undergo a considerable change. It is probable that we can devise a synchronising gear for a moving gun, but it is rather more likely that we shall devise a new type of aeroplane in which the propeller is not in the field of fire. A suggested design for such an aeroplane is shown in Fig. 3, where it will be seen that a propeller is put behind the pilot so that he obtains an unrestricted field of fire ahead.

Armour.

It is not proposed in this paper to deal with the advantages and disadvantages of armouring aeroplanes. It is sufficient to say that offensive aeroplanes must always be superior in performance to the aeroplanes that it is intended to attack, and the addition of armour will certainly reduce performance. It is more likely that the fighting aeroplane will remain almost or quite unarmoured and will depend upon its ability to dodge rather than upon its power to withstand rifle fire.

Size.

The size of aeroplane which is likely to be used on the air fighter in the future is a matter which cannot be settled easily. Certainly the smaller the aeroplane the quicker is it likely to manœuvre. At the same time, so long as a minimum size is necessary to carry the standard armament that appears necessary, it is always possible that a pilot of abnormal skill will be able, on a small aeroplane carrying little ammunition and perhaps a single gun, to outmanœuvre an aeroplane more heavily armed. The records of the Great War seem to show that the most successful aeroplanes on the whole were not the smallest. All we can say, then, is that the smallest size aeroplane that will carry the armament found by experience to be necessary is the aeroplane that should be used. The useful size appears to the writer to weigh in the neighbourhood of a ton, and taking 8 lbs. to the sq. ft. as the probable loading, this means a machine with about 280 sq. ft. of surface. An aeroplane of this size can be made extremely light to fly, and if the aspect ratio of planes is kept small, sufficient manœuvrability can be obtained to ensure that it is not appreciably slower in this respect than any other aeroplane.

Small aeroplanes are undoubtedly attractive, and there is always likely to be a peace-time tendency to encourage the making of aeroplanes which will not carry sufficient armament to render them really valuable war-time machines.

The horse-power that will be used will probably be the most that can be obtained from a motor weighing about 700 to 750 lbs. complete. What this will be the future will show. The writer thinks that in ten years' time it will be in the neighbourhood of 400, and that this power will be maintained to a height of at least 10,000ft.

The Fighting Aeroplane in the Future.

It is very unsafe to predict the development of aeroplanes. All sorts of new inventions and discoveries will help to improve the type. Looking perhaps ten years ahead, the writer thinks that we may look forward to the development of two separate and distinct types of single-seater fighters—one adapted for attacking enemy aircraft in one long dive and the other more suitable for combined work and "dog fighting." The former type is likely to remain rather similar to that now in use. It will probably be of the conventional tractor type and which should certainly be armed in such a way that the rate of fire will be at least 4,000 rounds per minute, while the ammunition carried is likely to be some 3,000 rounds. The speed of the aeroplane at 20,000ft. would be in the neighbourhood of 160 miles per hour, while diving from that height a speed of 300 miles an hour is likely to be attained. The rate of climb at 20,000ft. should be 1,000ft. per minute. Fuel for 2½ hours at economical speed will probably be sufficient. The duties of this type of aeroplane will be to patrol the skies and to pounce on any unfortunate aeroplane which is trying to carry out reconnaissance, bombing or other duties.

The other type of aeroplane that should be developed is one in which the pilot has a clear field of fire ahead and in which almost everything is sacrificed to rapid manœuvring. The guns should be mounted so that they are moved by some form of servo motor in accord with a sight. The rate of fire in this aeroplane is not quite so important, possibly 2,000 rounds per minute will be sufficient, and the amount of ammunition carried should be the same as in the previous case, namely, 4,000 rounds. The speed of this type is not so important and possibly 150 miles per hour at 10,000ft. will be enough. The climb, however, should be at least 2,000ft. per minute at that height, not with the idea of securing a high ceiling, as this machine will probably operate at comparatively low altitudes, but so as to get the maximum possible manœuvring power at any height. The amount of fuel to be carried is less certain and will probably be adjusted according to the ammunition carried or the performance required. The work of this aeroplane will probably be carried out in squadrons, and their duties will be to attack formations of enemy aircraft and to protect our own reconnaissance and bombing machines to some extent.

Two-Seater Fighters.

Two-seater fighters of the future are harder to forecast. It is not certain that it will pay to keep two-seater fighters solely as fighting machines. It is more likely that this type would be developed as reconnaissance machines capable of fighting, but this will depend upon the system of training adapted by the Royal Air Force. Unless the training is carried out so that the crew have implicit confidence in one another and are accustomed to team-work, this type of aeroplane is doomed to failure. The superior initiative of the single-seater fighter will be the deciding factor. If, however, the pilot knows and trusts his gunner, then improved moral may prove the turning point.

The question of moral enters largely into the problem. The value to an air force of having the recognised best fighting machine is possibly as important as the actual damage which these fighting machines can do. Happily for us the temperament of the men of this country seems to produce a large supply of pilots suited to the work, and so long as designers are able to produce aeroplanes worthy of their skill we have little to fear of losing our supremacy in this respect.

DISCUSSION.

The CHAIRMAN said they had listened to an interesting lecture, the earlier part of which had dwelt on that part of the history of the aeroplane that so many of them had worked in and the latter part on a forecast of the future of the fighting craft. There were many points in this very suggestive paper upon which the audience would have views based on their war experience as designers and fighting flyers, and he hoped that they would give expression to them. A number of gentlemen had sent in their names as intending to speak, but unfortunately the inclement British weather had kept some of them away. He would ask Major Buchanan to open the discussion.

Major BUCHANAN thought the Society was to be congratulated on having induced Major Green to record his experiences and his opinions of what the single-seater of the future ought to be. Air Force officers and designers did not agree very closely as to what the requirements of the future should be, and it was all to the good that men should come forward and put on record definite expressions of opinion so that other people who might think differently, or who might agree, could also record their opinions. The difficulty of single-seater work in the past had been to get a definite impression of what was required. During the war the conditions changed so rapidly that experience with any particular type under any particular conditions was not of long duration. He would like more information on a matter upon which he was not quite clear, viz., manœuvrability. The paper suggested, he believed, that the criterion of manœuvrability was the smallest circle in which an aeroplane could turn. He did not think the author really meant that, although it was one measure of it, because they might have two aeroplanes, one which turned in a larger circle than the other, but if the machine turning in the largest circle had the same angular velocity as the other, then for fighting purposes, at any rate, the other would come down if the latter were quicker in getting into the turn. He believed there were many fighting pilots present, and he hoped they would correct him if he were wrong, but his own opinion was that the criterion of manœuvrability was the speed at which an aeroplane could get into a turn, make the turn, and come out of it again. Another point he would like to raise was the question of the moment of inertia. He thought the author was quite right when he said that putting a pilot behind the main planes increased the moment of inertia and therefore was inclined to make it more difficult to manœuvre the machine. In the fore and aft direction this increase of the moment of inertia was of very little importance, but in other directions it was rather important, because it did affect the speed of getting into a turn. Another point was the vexed question of the amount of stability a single-seater required in the future. That question was discussed in most Air Force messes, but he did not think anyone had come to a very definite conclusion about it. The general conclusion seemed to be, from discussion with most officers of the Air Force, that a slight degree of positive stability was required. If Major Green divided the single-seater of the future into two types, viz., the high altitude and rush type on the one hand, the dog-fight type on the other, the stability required would vary with the particular type. He would very much like Major Green to give them the benefit of his experience on that subject because it was rather important and was one which was very much discussed. With regard to Major Green's final type of single-seater, being a conservative person he himself was rather in doubt. He should prefer to wait and see before saying very much about it. Major Green had emphasised the point that it was possible to train people to do things which were previously thought to be impossible. That was quite true, and Major Green had applied it to the training of the gunner, but it must not be forgotten that the same process of training would also govern pilots and enable them to manœuvre aeroplanes very much more rapidly than was considered possible at present, and it was possible that we might arrive at the same result by two different systems of intensive training.

Wing-Commander BOWEN, called on by the Chairman, said he had nothing to say.

The CHAIRMAN: There is the instrument side of the question.

Wing-Commander BOWEN said that on points like that they must remember that they had to cater for short service officers and it was absolutely essential that anything which was produced, however marvellous the results it gave might be, must be of such a nature that it could be manipulated by comparatively untrained personnel. It must be simple to use, and it must be what they called "fool-proof"; it was not a bit of good introducing stuff that was going to be complicated to use. In regard to the general position of the future, the policy seemed to be to produce a machine which would fulfil many functions, and do three or four different jobs in the same day. It might go out on ranging and spotting in the morning, long reconnaissance in the afternoon, and be called upon, perhaps, to carry mails in the evening, but whether the specialised machine would be a practical proposition for the future Air Force, with the financial limitations, he did not know. He was rather inclined to doubt it. In any case, they must always come back to the point that they had to produce something that must be used by a comparatively untrained personnel, otherwise the instant war broke out and they had to enlarge the Force, the whole thing would go to pieces if they had complicated stuff.

The CHAIRMAN: Now I want a pilot.

Squadron-Leader HOBART said he would like to speak about the two types which Major Green had discussed, viz., the one rather taking after the S.E.5 type, which would probably be used purely to dive on an enemy—the hit or miss type—and then climb again and dive again or give up the job and go straight home, as so many of the Huns did; and the other type, the dog-fighting machine, which on account of its superior manœuvrability would keep on the same level and win simply by manœuvrability. Personally he was rather doubtful whether manœuvrability alone was going to give the right machine for an offensive action. Manœuvrability very often meant that the machine was very excellent for defence but not for an offensive action. He thought that if the two types of machine were put up against each other to see which would win, the superior climbing one would win. It was not simply a question of shooting past the enemy, but it was a question of diving on to an enemy and climbing up again with the velocity gained in the dive. He knew of a case at the front in which one of our Sopwith Pups, with excellent manœuvrability, was dived down on by three Huns, one after the other, getting down to the level of the top of the Sopwith and climbing up again with the velocity gained in the dive. That was done in turn by each of the three Hun machines, so that there was always one machine diving, and they never gave the Sopwith a chance of getting out of a turn. In fact, the pilot had to keep on turning until the Huns got tired of it. It was a very nice type of machine, with manœuvrability like that, but it did not lend itself to a satisfactory offensive action, unless they had the climb as well. It was a very difficult point to decide how much manœuvrability one could sacrifice in order to get the climb in place of it. He believed that a lot of pilots would choose the machine with the superior climb and sacrifice manœuvrability, because an offensive action was based on climb provided manœuvrability was somewhere within ordinary limits.

Personally he was doubtful about a movable gun because he was an extremely bad shot himself, and he believed that the average pilot, even after several years of the war, would not do good shooting with a gun of that description. With two guns firing at the rate of from 400 to 600 per minute, it was astounding what the pilots missed. They often got right on to the tail of their objective and went on firing, and simply nothing happened at all, and one did not know where the shots were going. Towards the end of the war, when destruction of the enemy increased a great deal, he understood that it was

due entirely to the speeding up of the firing to 2,000 per minute, and he believed that was the sole cause of war pilots coming into the killing class where previously they were in the missing class. Personally he thought that if they could have two fixed guns and have manœuvrable machines and increase the number of rounds, and even increase the number of guns, so that they could have still more rounds in the air at the same time—he meant on a small machine, that would be the most destructive machine. He was not against the moving gun, but felt that it was only suitable for highly trained pilots. He thought it would be worth while having a few made to be tried by thoroughly experienced pilots. His point was that he felt that the average pilot would do better with a fixed gun.

Captain PAYN said the question of manœuvrability interested him particularly because he had, unfortunately, had a fairly large experience with recent machines. He shared Wing-Commander Bowen's opinion, as far as he was able to judge, on the question of moment of inertia. It did not seem to enter into it very much, but he thought the question of lateral control was a very pronounced one and limited a machine very much, assuming there was adequate rudder and elevator control. Rudder control they must have to cope with the manœuvrability necessary to effect slow landing in awkward circumstances, but at top speed or thereabouts, in manœuvring after a dive, he felt it was essential that lateral control should be good, and by good he meant that they should get a certain roll, and a machine which had that to a pronounced degree was essentially the more manœuvrable. As to the question of the use of the elevators, it would appear that a limit was reached purely by strength. Assuming that they had sufficient horse-power to give the necessary speed and rate of climb, which followed with it, the limit then appeared to be how far the pilot dared approach the maximum incidence at that particular speed, so that the machine did not break in the air. He would very much like to hear Major Green's views on that point. He was very interested to hear Major Green's prophecy for the coming years, but if development was to be so rapid would it be worth while making machines of such durability as he had suggested?

He shared the previous speaker's opinion that fixed guns and a manœuvrable machine giving a sufficiently large and intense zone of fire was the best. The general aiming should be done by the aeroplane, and accurate aiming would not be so necessary.

The CHAIRMAN said that if they were making a mass attack and had a number of ships against a lesser number of ships, the strength of the fire was increased in proportion to the square of the number. Two aeroplanes were four times as strong as one, and proportionately, provided they could attack. If they had 16 aeroplanes and could only fire at the target by going for it, they would meet, whereas if they could move their guns they could fire at the same time without meeting. They did not want them to meet.

Captain PAYN said he was only considering the single-seater type. It might be a better proposition to have the movable gun on a two or three-seater type of machine.

The CHAIRMAN said they might have single-seaters in mass formation, and if the enemy had movable guns, that might assist them to win as against single-seater machines with fixed guns.

Captain PAYN said that perhaps he had not given a very good answer, but he had not had a very great experience as a fighting pilot. It might be as the Chairman had said, but if the enemy's machines had a superior performance, the enemy would not worry after a very short time.

The CHAIRMAN said he was glad to have Captain Payn's answer, which he regarded as very valuable.

Captain PAYN, continuing, said that he also shared Squadron-Leader Hobart's view as to manœuvrability. One machine he had flown was extremely

good. It was fairly lightly loaded and they had great faith in its strength. They were able to pull it round to the limit of its capacity, until the wings were stalled. It was a D.H.2, and the guns were movably mounted. It was a wonderful machine in its day.

Wing-Commander CAVE-BROWNE-CAVE thought it was particularly valuable that Major Green should have come forward with a paper on the characteristics of fighting machines because it was a subject in which interest had to be artificially stimulated. Many people were interested in the characteristics of commercial machines, but it was, even in the Service, very difficult to get the characteristics of fighting machines even discussed. To make the discourse complete, there should be something dealing with the type of machine which would be used for fighting under naval conditions, and he did not know whether the Council would be able to get a companion paper on that question. He had been very interested in the expressions of opinion as to the demerits of moments of inertia. The Fire Prevention Committee were, he believed, pretty well satisfied that if it were possible to put petrol tanks on the wings of the machines some distance out, the probability of the machine being destroyed by fire when flying or in a crash would be very much reduced. It was almost certain that the tanks on the wings would, if ignited, blow out, and in any case the burning of the structure of the machine would be very much more gradual. He believed the accepted opinion at present was that an increase of the moment of inertia, with these tanks far out, would be a very serious handicap to the machine in fighting. The author had explained that what limited the manœuvrability of the machine at present was its strength, and that if they increased the moment of inertia they would not render more drastic manœuvres impossible. He believed that was so in the case of manœuvres in pitch, but he did not think it was the case in regard to manœuvres in roll or yaw, and he would be glad to have his opinion on that point. A totally different point was the question of training pilots. Although he had had absolutely no experience whatever as a fighting pilot he was inclined to agree with Major Green, rather than the fighting pilots who had spoken; for this reason, that the things which could be effected by training over a period of years, as distinct from the very intensive training which was all that was possible during the war, were so remarkable that he could not help feeling that the possible development of the human skill must necessarily be very great. The trouble was this; how were they going to carry out that training? He was at the Isle of Grain trying to devise a scheme of competing with the gunnery instruction school at Eastchurch in aerial fighting, but it was an extremely difficult thing to do. They were playing the stations around them at the various games, where the method of competition had been more or less reduced to a definite system, but how were they going to carry out the most important form of competition, viz., training in aerial fighting? The camera guns went a long way, but they would have to get something very much more satisfactory before they could reckon that the laws of aerial mock fighting were as satisfactory and realistic as the laws of boxing or of fencing. Until they could get a system of training which fairly satisfactorily produced the conditions of actual fighting, they missed two very valuable points. One was, they did not train their pilots in actual fighting, and when action came they felt strange and new to it. The other was that they could not effectively work out the merits of alternative types of machine because the expressions of opinions of pilots were not sufficiently certain or reliable even at this short period after the war for the fighting machines of the service to be developed solely by such expressions of opinion. There must be something a little bit more practical than pilots' experiences during the war using different types of machines. There were very few problems of greater importance to the development of fighting aircraft than the evolution of some artificial method of reproducing the actual process of aerial fighting. The question of the movable gun was primarily one of training the pilot. A mental development such as that which evolved the modern gunnery

officer from Nelson's master gunner should render possible in aerial fighting things much more complex than the moving gun.

Lieutenant-Colonel HECKSTALL SMITH, referring to the statement in the paper that Bach had written music which could not be played, said one could hardly ask an aeroplane designer to design a machine so that it required an infinite amount of technical skill to fly and would take years to learn. The whole crux of the design of the fighting aeroplane depended on the number of available pilots who were going through their training, and he noticed that in the lecture before the Royal Society of Arts given a short time ago by Sir Hugh Trenchard, he definitely stated that it was not any use training pilots in large numbers at the present time because they would be too old to be of any use in the next war. That was a definite statement and was very interesting because it meant to say that unless they could decide definitely on training for a number of years, they could not say how skilled the pilot was going to be, and therefore how delicate the fighting machine, which probably could be improved. That was what the designer had to make his design on, and unless he had some measure of knowledge of the skill to which pilots were going to be brought in numbers, it was no use going on designing machines to any great degree of delicacy such as Major Green had suggested. Experience was required, and Major Green had rightly pointed out how essential it was to have co-operation between the designers and the heads of the Air Force who were going to train the pilots, so that the machine of the future might be designed for the pilots of the future.

The CHAIRMAN said he would now call on Major Green to reply to the discussion as he was anxious not to form a precedent for exceeding the time or encroaching on the dinner hour. Any others who wished to contribute to the discussion were invited to send in their communications to the Secretary.

Major GREEN said that a number of points raised in the discussion were common to several speakers and that he would therefore answer some of them collectively. With regard to manœuvrability he thought he had made it clear that manœuvrability and climb were very much the same thing. He agreed with those speakers, therefore, who emphasised the importance of climb. He thought that pilots were a little apt to mix up manœuvrability and stability. An unstable machine unquestionably manœuvred itself extremely fast on certain occasions, and people were apt to think that a stable machine could not be manœuvred as fast as an unstable machine because it generally felt steadier. Personally, he did not think that a small margin of positive stability hindered manœuvrability, and at the same time he was definitely in favour of stability both for comfort and safety of flying, and also because it made a much steadier gun platform.

A machine which was intended to attack by diving should certainly be stable over its whole range of speed, while the highly manœuvrable machine was probably good enough if it were stable over its ordinary flying range. Stability did not involve any appreciable amount of weight. With regard to manœuvrability he agreed that turning was not the only point. He had taken this as an example and did not profess to discuss the question of manœuvrability to the full, as it would have made a long paper in itself. Speed of getting into the turn was very possibly the deciding factor, but so long as the aspect ratio of the machine was kept fairly small, he believed that the remarks he had made were correct.

Major Buchanan had said that the fore and aft moment of inertia affected rudder control. The speaker agreed that it did, and he had always failed to see why aeroplane designers used such small rudders. The amount of weight for a few extra square feet was small, and on machines of this size it was easy to balance the rudder to any required amount. He was convinced that rudders, on the whole, were made too small.

Wing-Commander Bowen, when asked his opinion, said he preferred to wait

and see. That was a safe thing to do; perhaps the speaker himself would have been wiser to have done it. The point that he had been trying to make was that the machines which the designer produced depended largely on the requirements of the R.A.F., and that the requirements of the R.A.F. depended on the sort of aeroplanes that they actually obtained. In this way we reached a deadlock, and it was necessary to have some sort of discussion periodically when both the R.A.F. and the designer could suggest seemingly impossible things for the other to do. In the general way the suggestions for difficult things came from the R.A.F., and it seemed only fair that the designers should suggest difficult things for the R.A.F. to do, such as the moving of the gun and the aeroplane at the same time. The speaker had suggested that the R.A.F. ought to use intensive training to enable pilots to handle aeroplanes in a way that was not now done. It was not suggested that aeroplanes suitable for this work should be ordered in large quantities. The suggestion was that it was worth while seeing whether training on these lines could not be developed, and the difficulty was not in carrying out the training so much as in finding out how to do it. If this was not done he did not believe it was possible to improve the fighting machine as otherwise might be done.

Wing-Commander Bowen had spoken of complication. The speaker agreed that complication should be avoided as far as possible, but that complication in aeronautics was inevitable. An aircraft engine was immensely complicated, and the sort of complication that had been suggested in the paper would be quite small compared with it. It was, after all, only a matter of degree.

Wing-Commander Bowen had also said that we must not have specialised machines. If we could afford to say that for a number of years we were going to have no more big wars, and he sincerely hoped that we should not, and if we are prepared to shape our policy on these lines, then many of the things he had said might be modified. It was necessary to be able to get ready in case of war as quickly as possible, and although we might not order specialised machines, we ought at least to keep them alive. It was a difficult problem, but if we could only find out how to do it we should have advanced a long way.

The third speaker said that manœuvring and climbing were bound up together, and in this he quite agreed. He also agreed that too many bullets went astray and that was the reason why he wanted to get a machine which would fire the maximum number of bullets in a given time. It was not suggested that we should neglect to train people with the fixed gun; in fact, all the ordinary training must be with the fixed gun, and he hoped that this would be carried out so that there would be as few missed shots as possible.

The speaker agreed with Captain Payn that lateral control is probably the biggest part of manœuvrability; it did not affect the question seriously whether the aeroplane was stable or unstable, and he did not think that quick lateral control demanded greater strength. The limit of strength came only when manœuvring in the fore and aft direction; quick banking did not affect the question seriously. Captain Payn had asked why we needed durable machines if everything was to be changed rapidly. The speaker had not suggested that aeroplanes would change rapidly. He had only pointed out the sort of thing that might happen if fighting machines were kept alive. We must always keep ahead with possible development in view of the possibility of war. Captain Payn had also said that a two or three-seater would be better because then they have a movable gun. This seemed to be begging the question. If a single-seater could be used with a movable gun it would be better because it costs less money and involves fewer pilots. It seemed probable that it was better to train one pilot well than a pilot and observer less well.

He was glad that Wing-Commander Cave-Browne-Cave had supported his view that the fighting aeroplane had got to be kept alive. There was always likely

to be a peace-time tendency to return to smaller aeroplanes although their use was not supported by experience during the Great War. With regard to petrol tank position, he did not know the exact importance of moment of inertia sideways. It had some influence, and he believed it could be calculated directly. It probably had the greatest influence at the beginning of the turn and afterwards very little.

Lieut.-Col. Heckstall Smith had said that the paper suggested using aeroplanes that could only be flown after years of training. This was hardly correct. The speaker had asked for an aeroplane that could not be fought to its best advantage except after long practice, but there was no reason why it could not be flown as easily as any other aeroplane.

Major BARLOW (*communicated*): There are two points I should like to bring forward bearing on this excellent paper by Major Green as a result of my experience at Martlesham Heath.

In discussing the all-important question of view, Major Green states that in his opinion the cutting away of the centre section top plane is bad for aerodynamic reasons. This is not borne out by actual tests. A Camel with the centre section partially cut out to give a better view has been found to have the same aerodynamic properties with, if anything, a slightly better performance. In confirmation of this, I should like also to refer to two aeroplanes designed by the Westland Aircraft Company, namely, the little "Wagtail" single-seater scout and the "Weasel" two-seater fighter. Both these have excellent view in the top hemisphere with cut-away top plane centre section, and I think I am quite at liberty to say both aeroplanes in their class and type can hold their own in performance and manœuvrability as fighting aircraft.

The second point is manœuvrability. In this I strongly support the remarks of Captain Payn. Undoubtedly lateral control is one of the deciding factors, and this is borne out by the extraordinary manœuvrability of an aircraft which all pilots will agree had a marvellous aileron control, *i.e.*, light, very quick and effective. I refer to the Fokker biplane. This aircraft had not a remarkable high rate of climb or speed, but the combination of wing section with its high efficiency controls have more than counteracted for this small deficiency in performance.

I should like to have heard Major Green's technical opinion on the possibilities of monoplane scouts with cantilever construction coming to the front again. However, the points raised in the paper should do much to help on this question of fighting aeroplane design, which I can assure the lecturer is constantly being discussed by the majority of pilots and technical officers of the R.A.F., certainly at English experimental stations.

ANSWER TO MAJOR BARLOW'S REMARKS COMMUNICATED IN WRITING.

Major Barlow states that cutting a hole in the top plane does not affect performance. This I find difficult to believe unless there was one peculiar reason connected with the aeroplane, such as the excessive interference between the top plane and the body. On all the tests that I have been able to carry out myself there has been a distinct loss of performance.

I quite agree with Major Barlow about manœuvrability. Good aileron control is certainly one of the deciding factors, but it certainly ought to be combined with a rudder of sufficient size.

With regard to monoplane scouts, I do not think that they are likely to have much future. It seems to me that a monoplane must have a bigger span than a biplane; hence the all-important lateral control is likely to be slower.

THE FAN PROPELLER AND BLADE INTERFERENCE.

BY M. A. S. RIACH, F.R.AË.S., ASSOC.INST.N.A.

For some time it has been recognised that the aerodynamical theory of the screw propeller, as at present presented, leaves considerable room for improvement. The leading specialists in this branch of aerodynamics, such as Mr. Fage, Mr. McKinnon-Wood and Dr. Watts, have given recognition to the all-important fact that a velocity of inflow can only be produced by the mutual interfering action of the propeller blades upon each other. Dr. H. C. Watts was, I believe, the first person to point this out clearly, and to show that the hitherto accepted theories of inflow rested upon a highly empirical basis. By "velocity of inflow" is meant the *additional* velocity required to modify the method of propeller analysis, known as the blade element theory, originally enunciated by S. Drzewiecki in 1892. The accepted and standard inflow theory of the airscrew, as, for example, given in Professor L. Bairstow's "Applied Aerodynamics," rests upon the empirical assumption that the ratio (velocity of inflow)/(velocity of impressed slip) is a constant for all propellers and for all radii along the propeller blade length. The numerical value of this ratio it has been left to experimental research to determine, but fundamentally it is nothing more nor less than an empirical factor of ignorance to be justified only by the sparcity of time and the pressure of work during the war period. It is time that a more rational, because more fundamental, theory was evolved. In attempting to produce such a theory I have started out with two basic postulates:—

(1) The blade element theory of Drzewiecki is correct, to a sufficient degree of approximation, *if blade interference be supposed to be non-existent.*

(2) The physical action of an airscrew may be represented, to a good degree of approximate accuracy, by incorporating with (1) the effects of blade interference.

I consider here only the special case of a propeller working without axial advance in a fluid, *i.e.*, what has been called the "static" case. The general case of propeller action is of necessity more difficult, and it is thought that the present paper will have achieved its object if it suggests a line of inquiry which may prove fruitful in the general case as judged by the results given by the theory in the static case of screw action.

It is well known that if any symmetrical body be moving uniformly through air at rest, some air will be pushed along in front of the body and continue to be pushed along so long as the action continues. Conversely, if air be moving past a body at rest, some of the air in the neighbourhood of the body will be slowed up and this will continue so long as the action lasts. In both cases the action upon the air, in the neighbourhood of the body, gives rise to a force which is known as the resistance of the body to the motion. If U be the velocity of the body relatively to the air a long way in front of it, and Σ be the velocity which the body impresses upon the air, then the change in energy per second in the relative air stream is $\frac{1}{2}$ (mass of air per second affected) $[U^2 - (U - \Sigma)^2]$, the resistance force is (mass of air per second affected) Σ, and the work done per second by the resistance force upon the air is (resistance) V, where V is the relative velocity between the body and the air *at* the body. Then if the work done by the body

upon the air is equal to the change in energy in the relative air stream, we have simply :—

$$\Sigma V = \tfrac{1}{2}\left[U^2 - (U - \Sigma)^2\right]$$

i.e., $V = U - \Sigma/2$, which gives the relative velocity *at* the body. Now the above is a very elementary conception and in practice the conditions are far more highly complex. It is intended by way of illustration only.

Consider now a more difficult case, the case of an aerofoil moving uniformly through air at rest or, conversely, air moving uniformly past an aerofoil at rest in it. The same general type of thing occurs here (Fig. 1).

I call γ the gliding angle of the aerofoil, so that: $\tan\gamma$ = drag/lift. Then it is seen that the component velocities, normal and tangential to the direction of the resultant force upon the aerofoil, are $U\cos\gamma$ and $U\sin\gamma$. We may, by way of illustration, consider the component velocity $U\sin\gamma$ to be analogous to the free wind velocity of the case already considered and then we may expect this velocity to be slowed up as it passes the aerofoil, the other component velocity $U\cos\gamma$ remaining unchanged in value.

The aerofoil, as it moves, pushes some air along with it, but principally downwards. Call this impressed velocity Σ, and let part of it be present *at* the aerofoil and call this part $\sigma\Sigma$. Then, if we pursued the same reasoning as before, we should find the value of σ to be one-half. At present we shall leave it indeterminate in value. Then the relative *component* velocity *at* the aerofoil is not $U\sin\gamma$, but $[U\sin\gamma - \sigma\Sigma]$ (Fig. 2).

Hence the resultant velocity *at* the aerofoil is now seen to be inclined to the free wind direction at an angle of ξ and to be equal to

$$W = \sqrt{U^2\cos^2\gamma + (U\sin\gamma - \sigma\Sigma)^2}.$$

Notice that this resultant velocity W at the aerofoil may be constructed either by the velocities $U\cos\gamma$ and $(U\sin\gamma - \sigma\Sigma)$, or by the velocities U and $\sigma\Sigma$. The component velocity $U\sin\gamma$ is slowed up as it passes the aerofoil by the amount of the impressed velocity $\sigma\Sigma$ so that the component relative velocity *at* the aerofoil is $(U\sin\gamma - \sigma\Sigma)$.

Call the angle of chord incidence to the free wind direction α_r. Now I want to consider a hypothetical case in which it is to be supposed that a quantity of uniformly deflected air moves past the aerofoil in relative motion and with the relative velocity W. Let the depth of this layer of air be Δ, and let the chord width of the aerofoil element over which this air is supposed to flow in a two-dimensional motion be b. Call $b/\Delta = \delta$. Then I propose to show that this ratio δ may be regarded tentatively as a general constant.* Consider an element of aerofoil surface of span dx. Then the volume of air flowing over this element per second will be ΔdxW, its mass per second will be $\rho\Delta dxW$, and the resultant force upon the aerofoil element will then be $\rho\Delta dxW\Sigma$. Now write down the aerodynamical equation for the resultant force. It is

$$\sqrt{k_y^2 + k_x^2}\rho b dx U^2,$$

where k_y and k_x are the coefficients of lift and drag respectively and ρ is the mass/density of the air. Then

$$\rho\Delta dxW\Sigma = \sqrt{(k_y^2 + k_x^2)}\,\rho b dx U^2$$

$$i.e.,\quad W\Sigma = \sqrt{(k_y^2 + k_x^2)}\,\delta U^2,$$

which defines δ. Also

$$\tan\xi = (\sigma\Sigma\cos\gamma)/(U - \sigma\Sigma\sin\gamma) \quad \text{(see Fig. 2)}.$$

Hence

$$\sigma\Sigma\cos\gamma = (U\tan\xi)/(1 + \tan\gamma\tan\xi),$$

and

$$\therefore\ (W/\sigma)(U\tan\xi)/(1 + \tan\gamma\tan\xi) = k_y\delta U^2,$$

$$\because\ \sqrt{(k_y^2 + k_x^2)} = k_y\sec\gamma.$$

* It will be seen later that this is not strictly necessary.

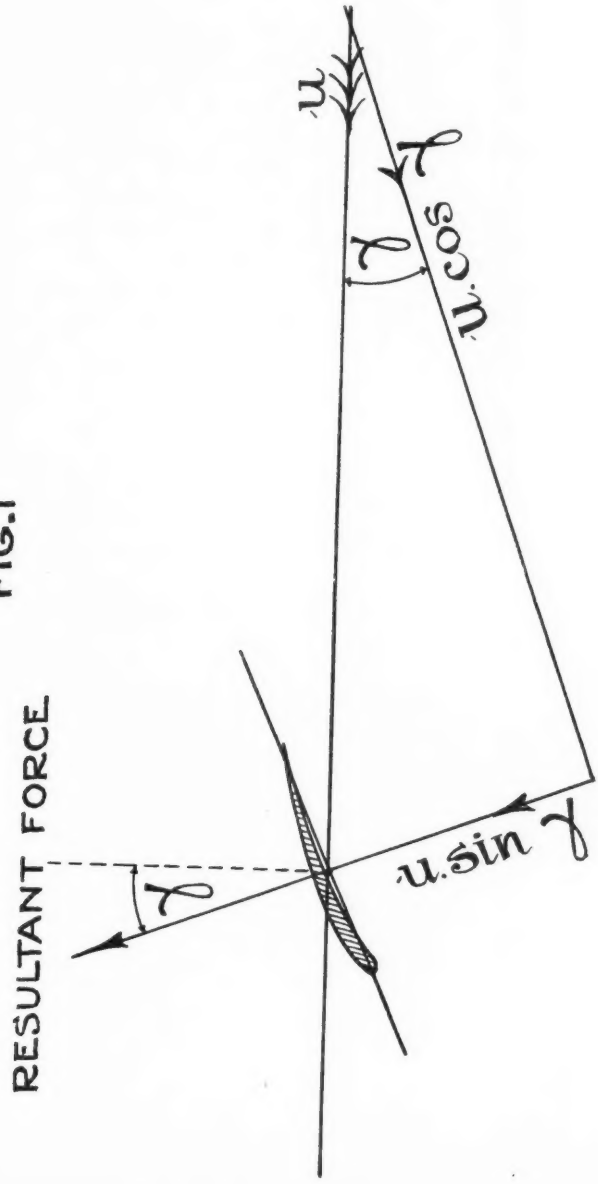
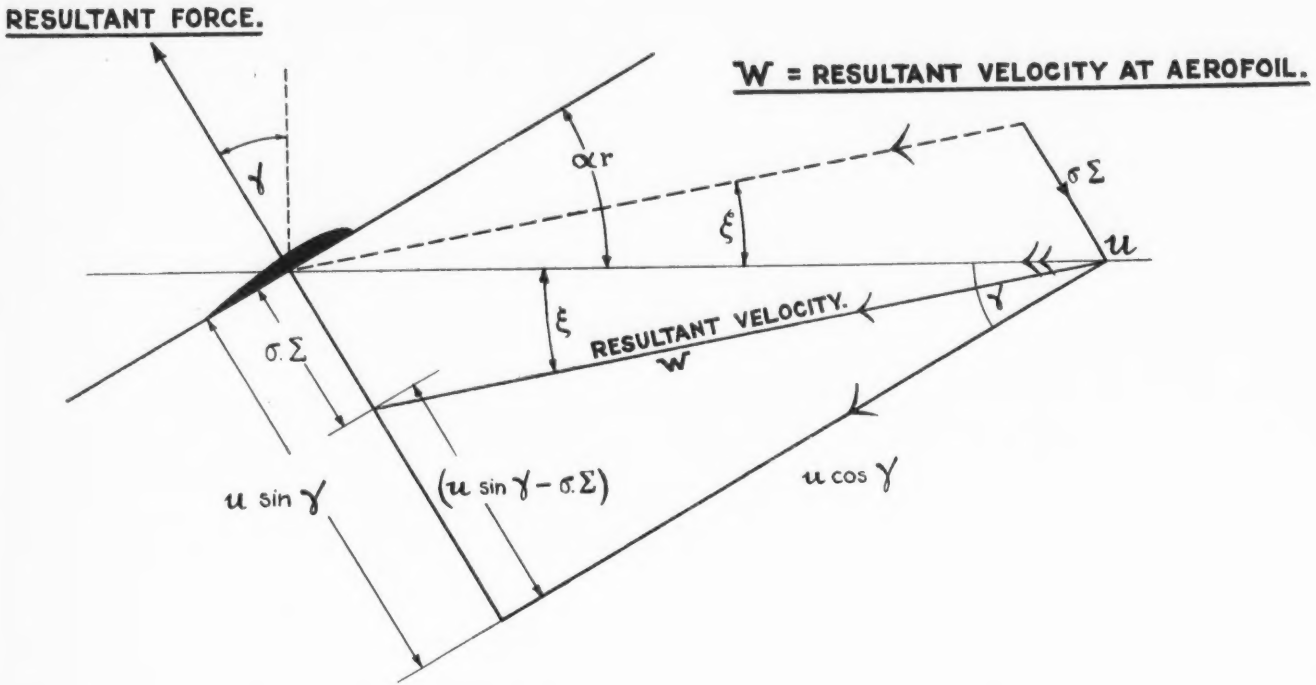


FIG. 1

FIG. 2.


RESULTANT FORCE.
W = RESULTANT VELOCITY AT AEROFOIL.
γ
αr
σΣ
ξ
u
ξ
RESULTANT VELOCITY.
W
γ
σ.Σ
u sin γ
(u sin γ − σ.Σ)
u cos γ

Further,

$$W = U/\cos\xi\,(1 + \tan\gamma\tan\xi) \quad \text{(see Fig. 2)}.$$

And

$$\therefore\ (1/\sigma)/(U^2\tan\xi\sec\xi)/(1 + \tan\gamma\tan\xi)^2 = k_y\delta U^2$$

$$i.e.,\ (\tan\xi\sec\xi)/(1 + \tan\gamma\tan\xi)^2 = \sigma k_y\delta$$

or alternatively since $\tan\gamma = k_x/k_y$;

$$(\tan\xi\sec\xi\,k_y)/(k_y + k_x\tan\xi)^2 = \sigma\delta.$$

Now for the angles with which we shall have to deal, ξ is always a small angle so that we can write approximately :—

$$(\pi/180)\,\xi k_y/[k_y + k_x\,(\pi/180)\,\xi]^2 = \sigma\delta$$

Solving the quadratic for ξ we get to the same degree of approximation :—

$$\xi = k_y\delta\sigma\,(180/\pi)/(1 - 2k_x\sigma\delta)$$

Now it is known, from experiments on "downwash" angles, that the angle of downwash varies as the lift coefficient almost exactly, *i.e.*, that $\xi = \Omega k_y$, where Ω is a constant for the aerofoil shape. Hence, $\Omega = (180/\pi)\,\delta\sigma/(1 - 2\delta\sigma k_x)$, and $(\sigma\delta k_x)$ is small compared to unity, so that we may conclude that $\sigma\delta$ is a constant† and, if σ be a general constant, then δ is a constant and tentatively may be assumed to be approximately a general constant.

This point, as already mentioned, I wished to demonstrate. The value of Ω has been found by experiment to be about 20 in round numbers, so that we can conclude tentatively that a value of $\sigma\delta = \pi/9$ is of the right order. Note in passing that, δ being a ratio and the quotient of two linear quantities, its value can change only through change of the angle of incidence if it changes at all—change of chord width for example cannot affect its value because the type of flow round two geometrically similar aerofoils of different size is the same for equal incidence angles, except for small $[vl]$ effects which can presumably be ignored at the high speeds encountered in propeller action.

Hence, by substitution, we get to the same degree of approximation the value of Σ given by

$$\Sigma = \{\,U\delta\sqrt{(k_y^2 + k_x^2)}\,\}\,/(1 - \sigma\delta k_x);$$

so that the total impressed velocity Σ is seen to vary as the free wind velocity and as the lift coefficient for most angles of incidence approximately.

Application to Propeller Theory.

To successfully study the mutual interfering action of the propeller blades upon each other it is necessary to consider them as forming an infinite series of equal members equally spaced apart and to consider the conditions at any member of the series which is far removed from the first member. We study here the cascade series corresponding to any one element of a blade of course. We make the assumption that the conditions at the rth member of the series become "steady" as r is increased indefinitely, and by this definition of "steady" we mean that the conditions *at* and *after* the rth member are all *identical*. We do not, however, imply that the air flow is uniform round the circumference of any annulus in the screw disc, it is probably different at the blades to anywhere else in the annulus, but we assume that it is the same at any one blade as at any other blade (at equal radii of course). Such non-uniformity in the airflow round any annular circumference gives rise to the familiar "gustiness" associated with all propeller action. Consider Fig. 3, which represents a cascade series of equal and equally spaced aerofoil elements.

By our definition of a "steady" state and by our assumption that such a state exists *at* and *after* the rth member of the above series, we know that the inflow velocities at all the members of the series, *at* and *after* the rth member,

† This is the important deduction.

are *identical*. These inflow velocities are produced by the action of the $(r-1)$ members of the series, from and including the $(r-1)$th member up to the first member of the series. They are the "legacies" of the *impressed* velocities produced by these $(r-1)$ aerofoils. Now since r is a very large number, it is not to be expected that the action of the *first* member of the series will have any *appreciable* effect upon the rth member. If we consider the aerofoils above to be moving with uniform speed C, from left to right through air at rest, it is evident that by the time the rth member has reached the position aa' the impressed velocity produced by the first member will have practically died out and so have no appreciable action (in producing a speed of inflow) upon the rth member. The same thing applies to the second, third, fourth, etc., members of the series. But when we get close enough to the rth member the "neighbouring" members *do* have an appreciable effect upon the rth member in producing a speed of inflow, *i.e.*, the $(r-1)$th, $(r-2)$th, etc., members have such an appreciable effect. So that what we have virtually to try and do is to *sum* a series having an infinite number of continuously decreasing terms. How are we to effect this without knowing the series to be summed? I suggest the following process as being extremely simple and having a rational basis. To begin with, the sum to infinity of the series is finite, for if not we should have an infinite speed of inflow which is absurd. Hence, we may define a number q (not necessarily integral) which shall represent the "mean" value corresponding to the sum to infinity. The definition of q is:—

$$q = \frac{\text{speed of inflow at } r\text{th member}}{\sigma \text{ (impressed velocity of } r\text{th member)}}$$

That is, if

Σ_r = impressed velocity of rth member,

and

$\sigma\Sigma_r$ = the proportion of this velocity *at* the rth member,

and if

Σ_s = speed of inflow at rth member,

then q is defined by

$$q = \Sigma_s / \sigma\Sigma_r, \text{ } i.e., \text{ } \Sigma_s / \Sigma_r = \sigma q = \text{inflow/slip ratio.}$$

In other words, what number multiplied by the impressed velocity *at* the rth member will represent the sum to infinity of *all* of the impressed velocities *at* all the members from the $(r-1)$th up to the first inclusive? The answer is q, which is thus defined—

Consider the $(r+q)$th term.

Since the times taken for the $(r+q)$th term to move into the positions initially occupied by the $(r+q-1)$th, $(r+q-2)$th, . . . rth terms are *small*, provided q is small compared to r, the velocities impressed by the rth, $(r+1)$th, . . . $(r+q-1)$th terms will not be sensibly different in value to the impressed velocities *at* these terms by the time the $(r+q)$th term has moved over all the positions initially occupied by these terms. This is only another way of looking at the *definition* of q. Now obviously the value to be assigned to q is not necessarily integral and will in general depend upon the value of the ratio $2\pi x/Nb$, where x is the blade radius, N the number of blades, $2\pi x/N$ the "spacing" or distance apart of the members of the cascade series, and b the chord width of each member. I now introduce a convention regarding q, for the sake of simplicity only and as a first tentative estimate as to its probable value which may later be discarded if required without interfering with the general theory developed here. q is defined as the number of equivalent members of the series which may be looked upon as producing the inflow speed at the final member next to them (to the left, Fig. 3). Hence, consider Fig. 4.

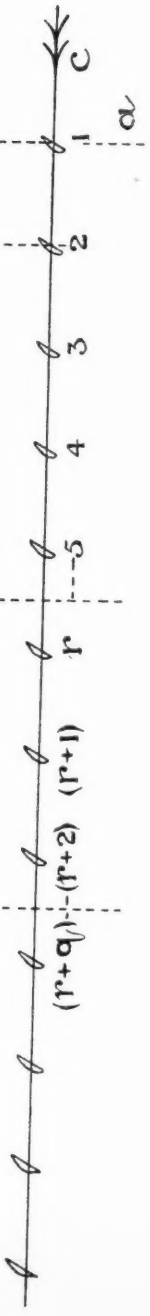

C
a
a
$\frac{2\pi x}{n}$
1
2
3
4
5
r
(r+1)
(r+2)
(r+q)-1
(r+q)th

FIG.3

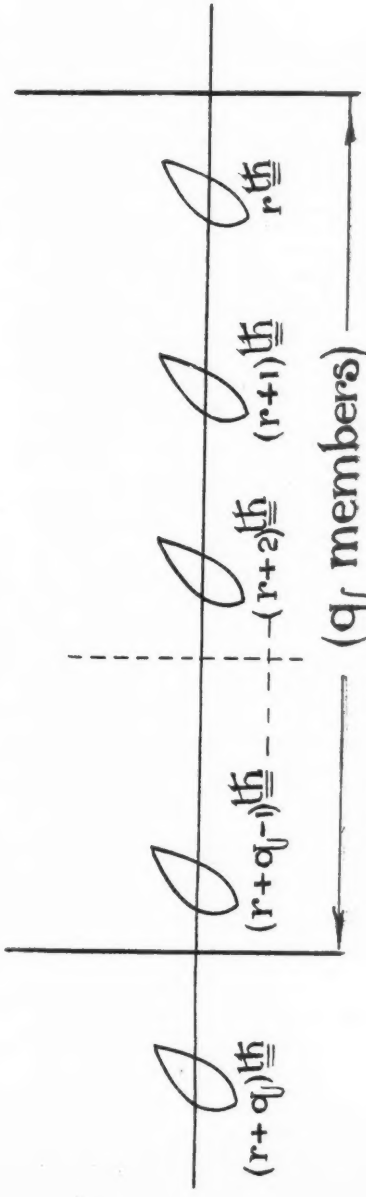

rth
(r+1)th
(r+2)th
(r+q-1)th
(r+q)th
(q members)

FIG.4

Suppose that we crowd in some more members between the rth and the $(r + q - 1)$th members, so that the new arrangement of *all* the members (new and old) is still an equally spaced arrangement and all the members are identical. Then, by my convention, I suppose that the *effective* number of members which now affect the $(r + q)$th member is simply equal to the *total* of the members from r to $(r + q - 1)$, *i.e.*, the sum of the old and new members. And similarly, if we thin out the original arrangement and decrease the total number of members from r to $(r + q - 1)$. Then the total distance from r to $(r + q - 1)$ being $2\pi xq/N = 2\pi xbq/Nb$, I suppose by this convention that $2\pi xq/N$ is always of the same value so long as the value of b remains the same. Now evidently if we increase b we get the same effect as by crowding in more members, for then the "spacing" chord width ratio becomes smaller in the same way as by increasing the number of members. Hence, if we are to include the chord width b in our convention for q we must make $2\pi xq/Nb$ = constant. This is what we do and this then constitutes the convention regarding the value of q. Hence,

$$q = Nb \text{ (constant)}/2\pi x = k\,(Nb/x).$$

Hence now :—

Ratio (inflow speed)/(impressed slip speed) $= \sigma q = \sigma k\,(Nb/x)$.

Then for most general designs of propeller blade shapes this ratio decreases as the radius increases and vice-versa, becoming infinite in value at the propeller boss. The type of curve of variation is very similar to that found experimentally by McKinnon Wood at the R.A.E. in his cascade experiments. The theory is seen to be in good agreement with experiment.

Now consider the conditions at the $(r + q)$th aerofoil (Fig. 5) where the flow is "steady."

Let the angle of the aerofoil element to the horizontal (*i.e.*, the plane of rotation of the propeller) be α. Then the inflow velocity Σ_s makes the *real* angle of incidence of the aerofoil α_r. C is the velocity of the element due to its rotation (the circumferential velocity) and is the same as the velocity C of Fig. 3. U is the free wind velocity of the aerofoil. W is the relative velocity *at* the aerofoil. γ is the gliding angle of the aerofoil at an incidence of α_r. The velocities $\sigma\Sigma_r$ and Σ_s lie *at the same angle* because the motion is "steady," and Σ_s is the sum of a number of equal $\sigma\Sigma_r$'s.

We can now find the value of α_r, the real angle of incidence of the aerofoil element. From the geometry of Fig. 5 we have :—

$$\text{Sin}\,(\alpha - \alpha_r) = \{\,\Sigma_s \cos(\gamma + \alpha - \alpha_r)\,\}/U$$

But $\Sigma_s = \sigma q \Sigma_r$, and Σ_r is the same as the Σ of the simple aerofoil considered at the beginning of this paper. Hence :—

$$\Sigma_r = \{\,U\delta\sqrt{(k_y^2 + k_x^2)}\,\}/(1 - \sigma\delta k_x) = (U\delta k_y \sec\gamma)/(1 - \sigma\delta k_x)$$

and

$$\therefore \sin(\alpha - \alpha_r) = \{\,\sigma q U\delta k_y \sec\gamma \cos(\gamma + \alpha - \alpha_r)\,\}/(1 - \sigma\delta k_x)\,U$$

$$i.e., \tan(\alpha - \alpha_r) = (\sigma q \delta k_y)\,[1 - \tan\gamma \tan(\alpha - \alpha_r)]/(1 - \sigma\delta k_x)$$

and

$$\therefore \tan(\alpha - \alpha_r) = (\sigma q \delta k_y)/\{\,1 - \sigma\delta k_x\,(1 - q)\,\}$$

But to the same degree of approximation previously employed this becomes :—

$$(\pi/180)\,(\alpha - \alpha_r) = (\sigma q \delta k_y)/\{\,1 - \sigma\delta k_x\,(1 - q)\,\}$$

which gives the value of α_r in terms of q, since $k_y = f(\alpha_r)$.

Now we can further simplify this result by assuming an equation for k_y in terms of α_r. For many types of aerofoils it is found that the lift coefficient is nearly a straight line from the angle of no-lift up to the stalling angle, so that let us put $k_y = m\,(\alpha_r - \beta)$, where m is a constant for the aerofoil defined by

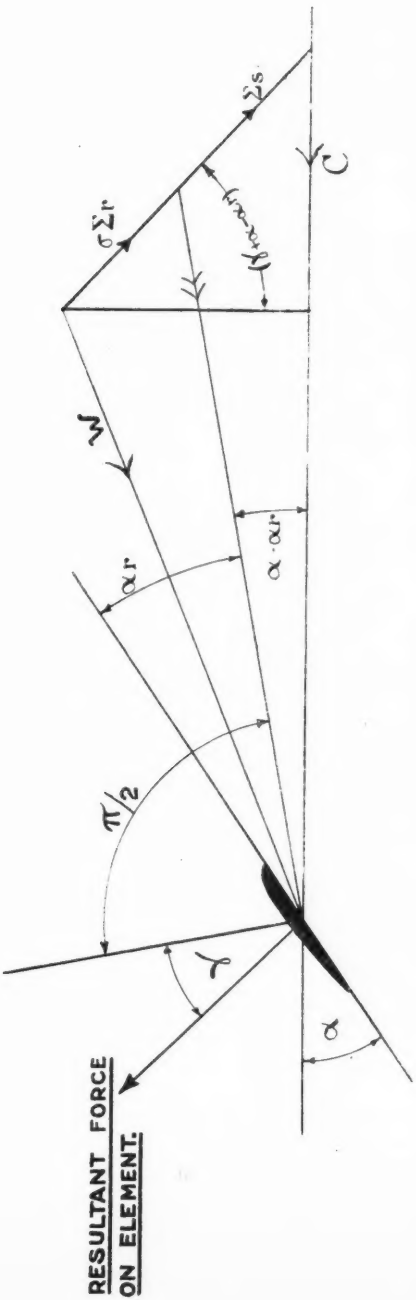


FIG. 5.

$\delta k_y/\delta a_r = m$, and β is the angle at which k_y vanishes, *i.e.*, the angle of no-lift of the aerofoil.

Then

$$(\pi/180)(a - a_r) = \{ \sigma q \delta m (a_r - \beta) \} / \{ 1 - \sigma \delta k_x (1 - q) \}$$

Now k_x appears in the denominator and is associated with a term having a very small value compared to unity, unless q is very large in value. Hence, we can tentatively neglect this term and write sufficiently approximately :—

$$(\pi/180)(a - a_r) = \sigma q \delta m (a_r - \beta)$$

giving

$$a_r = (a + \lambda q \beta)/(1 + \lambda q)$$

where

$$\lambda = (180/\pi)\sigma \delta m.$$

This is the general solution for a_r for the static case of propeller action.

Now before we can find the numerical value of a_r in any case we require to know the value of $q\lambda$, *i.e.*, the value of $q\sigma\delta$, since the value of m is known from the aerofoil shape. This unknown product can be settled experimentally if we make the substitution for q :—

$$q = k(Nb/x), \text{ so that } q\sigma\delta = \sigma\delta k (Nb/x).$$

And we can find the value of $\sigma\delta k$ from our experiment. Then, knowing the value of $\sigma\delta k$, we know the value of $q\sigma\delta$ in any case and hence know the value of a_r in any case. Note that q, σ and δ do not change in value with change of the angle of incidence.*

Consider now for a moment the derivation of q. The inflow velocity at any member of the series after the $(r + q)$th member is constant and is the sum of a certain (variable) number (q) of the impressed velocities *at* the members immediately in front (to the right) of it (Fig. 4). Thus, the inflow velocity at the $(r + q)$th member is the sum of the impressed velocities *at* the $(r + q - 1)$th, $(r + q - 2)$th, . . . rth members. And the inflow velocity at the $(r + q + 1)$th member is the sum of the impressed velocities *at* the $(r + q)$th, $(r + q - 1)$th, . . . $(r + 1)$th members. Hence the inflow speed at any member after the $(r + q)$th member is simply the sum of the impressed velocities *at* the q members immediately in front of it, and the point to notice is that this does not in general involve in this sum the impressed velocity at *any one* member such as the rth member. If we take a member sufficiently far down (to the left of) the series after the $(r + q)$th member, the impressed velocities *at* the rth, $(r + 1)$th, etc., members do not contribute to the inflow speed at the member chosen because they are too far away to affect it. So that if we now ask the question, what is the speed of indraught (total flow speed) at *any* point on the circumference of any annulus on the disc circle, we cannot say it is the same thing as the indraught at any blade element because the indraught here is the sum of the inflow speed and the impressed speed *at* the blade element, which *impressed* speed forms a part of the *inflow* speed at the *next* blade element round the annulus. So that it seems probable that the indraught speed into any annulus is a maximum at the blade elements and a minimum between the blades. However, in view of the constancy of the inflow speed and the remarks made above, it seems reasonable to suppose that the *mean* indraught into any annulus approximates to the *inflow speed* and that the indraught speed at the blade elements is *very local* and falls off rapidly to the inflow speed value even close to the blade elements, which value it maintains over the annular circumference until the next blade element is reached when it again rises in value to the sum (inflow speed + impressed speed). Fig. 6 illustrates what is meant. We shall then tentatively assume the *mean* speed of indraught into any annulus on the disc circle to be approximately equal to the

* Strictly this should read "q and $\sigma\delta$, etc."

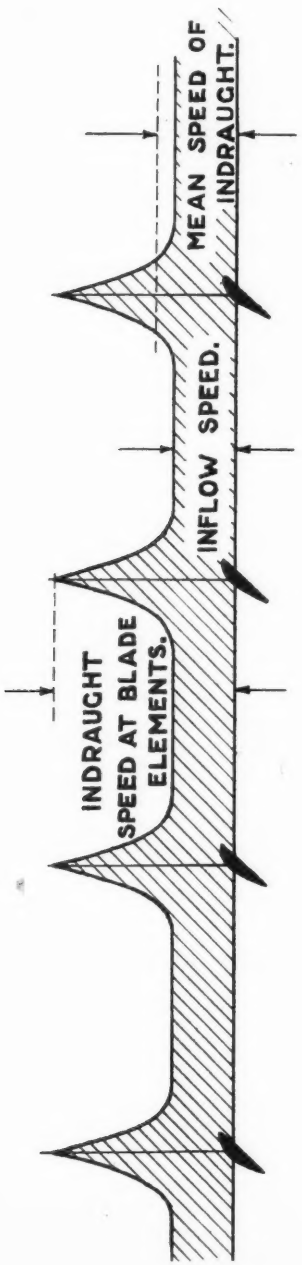


FIG. 6.

ANY ANNULAR CIRCUMFERENCE ON DISC CIRCLE.

inflow speed at the blade elements for the same radii.* Notice, in passing, that if the angle of incidence a_r is equal to

$$a_r = \{ a + \tfrac{1}{2}\delta m\beta\,(180/\pi) \} / \{ 1 + \tfrac{1}{2}m\delta\,(180/\pi) \}$$

which is quite a possible value, for we have already seen that $\sigma\delta = \pi/9$ is of the right order of value and we know that the value of σ lies between zero and unity, so that the value of δ lies between infinity and $\pi/9$, giving :—

$$a_r = \beta, \text{ when } \delta = \text{infinity}$$

$$\text{and } a_r = (a + 10m\beta)/(1 + 10m), \text{ when } \delta = \pi/9.$$

A usual value for m being $m = .05$, we get :—

$$a_r = (a + \tfrac{1}{2}\beta)/1.5 \text{ or } a_r = \beta$$

as the two extreme cases. Neither of these extreme cases, and therefore no case intermediate between them, is in any way an impossible one, so that the above solution for a_r is quite a reasonable one. But this solution for a_r corresponds to $\sigma q = \frac{1}{2}$, *i.e.*, it corresponds to the inflow/slip ratio, having a value of one-half. This value is of the right order and will be familiar to students of the old "inflow theory." Hence, again we notice that the theory given here gives results of the right order in value. We can now find the values of the axial thrust and the torque of the whole propeller. We write dT for the thrust and dQx for the torque on the blade element. The total thrust of the propeller is then :—

$$NT = N \int (\delta T/\delta x)\, dx,$$

and the power

$$NH = 2\pi nN/550 \int (\delta Q/\delta x)\, x dx$$

in the lb. ft. sec. system of units. So that we now proceed to find $\delta T/\delta x$ and $\delta Q/\delta x$. From Fig. 5 it is evident that

$dT = dR \cos(\gamma + a - a_r)$, where dR = resultant force on blade element,

and $dR = k_y \sec\gamma \rho b dx U^2$, by the ordinary aerofoil equation.

Hence, $dT = \cos(a - a_r)\,[1 - \tan\gamma \tan(a - a_r)]\, k_y \rho b dx U^2$,

i.e., $\delta T/\delta x = \cos(a - a_r)\,[1 - \tan\gamma \tan(a - a_r)]\, k_y \rho b U^2$.

But from the geometry of Fig. 5 we have :—

$$U \sin(a - a_r) = \Sigma_s \cos(\gamma + a - a_r)$$

and

$$U \cos(a - a_r) = C - \Sigma_s \sin(\gamma + a - a_r)$$

and

$$\therefore \tan(\gamma + a - a_r) = \{ C - U \cos(a - a_r) \} / \{ U \sin(a - a_r) \}$$

giving

$$U = C/\{ \cos(a - a_r) + \sin(a - a_r) \tan(\gamma + a - a_r) \}$$

This gives :—

$$U = C \cos(a - a_r)\,[1 - \tan\gamma \tan(a - a_r)]$$

and

$$\therefore \delta T/\delta x = \cos^3(a - a_r)\,[1 - \tan\gamma \tan(a - a_r)]^3\, k_y \rho b C^2,$$

$$i.e., \delta T/\delta x = C^2 k_y \rho b \{ 1 - \tan\gamma \tan(a - a_r) \}^3 / \{ 1 + \tan^2(a - a_r) \}^{3/2}$$

$$= C^2 k_y \rho b \{ 1 - 3 \tan\gamma \tan(a - a_r) \} / \{ 1 + 3/2 \tan^2(a - a_r) \}$$

Approximately, since both $\tan\gamma \tan(a - a_r)$ and $\tan^2(a - a_r)$ are small compared to unity.

Hence

$$\delta T/\delta x = C^2 \rho b \{ k_y - 3k_x \tan(a - a_r) \} / \{ 1 + 3/2 \tan^2(a - a_r) \}$$

$$= C^2 \rho b \{ m(a_r - \beta) - k_x (\pi/60)(a - a_r) \} / \{ 1 + (3/2)(\pi/180)^2 (a - a_r)^2 \}$$

* This assumption is not required for the theory generally. It is used only in evaluating θ in the last part of the Paper.

to the same degree of approximation as before, and substituting for k_y in terms of α_r in the approximate equation :—

$$k_y = m\,(\alpha_r - \beta)$$

Hence $(\delta T/\delta x)$ is found in terms of the radius (x) and the angle (α_r), which latter is known already in terms of the angle of the blade and q. The values of $(\alpha_r - \beta)$ and $(\alpha - \alpha_r)$ are then evidently :—

$$\alpha_r - \beta = (\alpha - \beta)/(1 + \lambda q);$$

and

$$\alpha - \alpha_r = \{\, \lambda q\,(\alpha - \beta)\,\} \,/\, \{\, 1 + \lambda q\,\}$$

Then by substitution :—

$$\delta T/\delta x = C^2 \rho b\,(\alpha - \beta)\,(1 + \lambda q)\,\{\, m - (\pi/60)\,k_x \lambda q\,\} \,/$$
$$\{\, (1 + \lambda q)^2 + (3/2)\,(\pi/180)^2\,\lambda^2 q^2\,(\alpha - \beta)^2\,\}$$

giving $(\delta T/\delta x)$ in terms of λq, etc.

Now

$$\lambda q = (180/\pi)\,\sigma\delta m k\,(Nb/x)$$
$$= (180/\pi)\,m\,(Nb/x)\,\sigma\delta k$$
$$i.e.,\ \lambda q = (180/\pi)\,m\,(Nb/x)\,\theta,$$

say where

$$\theta = \sigma\delta k.$$

So that θ, or $\sigma\delta k$, becomes now the only unknown quantity in the equation. Since also the term $(\pi/60)\,k_x \lambda q$ is small compared to the term (m) because it is of equal ratio to (m) to the ratio

$$k_x\,(\pi/60)\,(\alpha - \alpha_r)/k_y$$

which is small compared to unity, except for the case when k_y is in the neighbourhood of β the "no lift" angle—an ordinary value being of the order of 1/15—we may in many cases treat it only as of the order of a correction and hence assume the value of k_x to be constant with the blade radius. This is a simplification in many cases.

Then substituting for λq in $\delta T/\delta x$, we get :—

$$\delta T/\delta x = C^2 \rho b m\,(\alpha - \beta)\,\{\, 1 + \theta\,(180/\pi)\,m\,(Nb/x)\,\}\,\{\, 1 - 3\theta k_x\,(Nb/x)\,\} \,/$$
$$[\,\{\, 1 + \theta\,(180/\pi)\,m\,(Nb/x)\,\}^2 + (3/2)\,\theta^2 m^2\,(\alpha - \beta)^2\,(Nb/x)^2\,]$$

This is the formula for the axial thrust of any type of fan. The only unknown quantity is seen to be θ, and later the value of θ will be determined to a first approximation.

By a similar process we now proceed to find the value of the torque, *i.e.*, we find the expression for $\delta Q/\delta x$. The circumferential component of the force reaction on any blade element is given by :—

$$dQ = dR \sin(\gamma + \alpha - \alpha_r)$$
$$= \sin(\gamma + \alpha - \alpha_r)\,k_y \sec\gamma \rho b dx U^2$$
$$i.e.,\ \delta Q/\delta x = \cos(\alpha - \alpha_r)\,[\tan\gamma + \tan(\alpha - \alpha_r)]\,k_y \rho b U^2$$
$$= \cos^3(\alpha - \alpha_r)\,[\tan\gamma + \tan(\alpha - \alpha_r)]\,k_y \rho b U^2\,[1 - \tan\gamma\tan(\alpha - \alpha_r)]^2$$
$$= C^2 k_y \rho b\,\{\, \tan\gamma + \tan(\alpha - \alpha_r)\,\}\,\{\, 1 - \tan\gamma\tan(\alpha - \alpha_r)\,\}^2 /\,\{\, 1 + \tan^2(\alpha - \alpha_r)\,\}^{3/2}$$
$$i.e.,\ \delta Q/\delta x = C^2 k_y \rho b\,\{\, \tan\gamma + \tan(\alpha - \alpha_r)\,\}\,\{\, 1 - 2\tan\gamma\tan(\alpha - \alpha_r)\,\} \,/$$
$$\{\, 1 + (3/2)\tan^2(\alpha - \alpha_r)\,\}$$

Approximately as before,

$$i.e.,\ \delta Q/\delta x = C^2\rho b\ \{\ k_x + k_y \tan(\alpha - \alpha_r)\ \}\ \{\ k_y - 2k_x \tan(\alpha - \alpha_r)\ \}\ /$$
$$k_y\ \{\ 1 + (3/2)\tan^2(\alpha - \alpha_r)\ \}$$
$$= C^2\rho b\ \{\ k_x + m(\pi/180)(\alpha_r - \beta)(\alpha - \alpha_r)\ \}\ \{\ m(\alpha_r - \beta) - k_x(\pi/90)(\alpha - \alpha_r)\ \}\ /$$
$$m(\alpha_r - \beta)\ \{\ 1 + (3/2)(\pi/180)^2(\alpha - \alpha_r)^2\ \}$$

substituting as before. Then

$$\delta Q/\delta x = C^2\rho b\ \{\ k_x(1 + \lambda q)^2 + m(\pi/180)\lambda q(\alpha - \beta)^2\ \}\ \{\ m - k_x(\pi/90)\lambda q\ \}\ /$$
$$m\ \{\ (1 + \lambda q)^2 + (3/2)(\pi/180)^2\lambda^2 q^2(\alpha - \beta)^2\ \}$$

Hence, substituting for λq as before, we get finally :—

$$\delta Q/\delta x$$
$$= C^2\rho b\ [k_x\ \{\ 1 + \theta(180/\pi)\, m\,(Nb/x)\ \}^2 + m^2(\alpha - \beta)^2\,\theta\,(Nb/x)]\ [1 - 2k_x\theta\,(Nb/x)]\ /$$
$$[\ \{\ 1 + \theta(180/\pi)\, m\,(Nb/x)\ \}^2 + (3/2)\, m^2(\alpha - \beta)^2\,\theta^2\,(Nb/x)^2]$$

This is the formula from which the power is obtained for any type of fan, the torque being $\int x\,(\delta Q/\delta x)\,dx$ for each blade. As for the axial thrust formula, the only unknown quantity is θ.

Experimental Determination of θ.

It is evident that $\Sigma_s = C \sec\gamma \sin(\alpha - \alpha_r)$. And the vertical component, *i.e.*, the component velocity normal to the screw disc, of Σ_s is $\Sigma_s \cos(\gamma + \alpha - \alpha_r)$. Hence, denoting this normal velocity component by Σ_s', we have :—

$$\Sigma_s' = \Sigma_s \cos(\gamma + \alpha - \alpha_r)$$
$$= C \tan(\alpha - \alpha_r)\ \{\ 1 - \tan\gamma \tan(\alpha - \alpha_r)\ \}\ /\ \{\ 1 + \tan^2(\alpha - \alpha_r)\ \}$$
$$i.e.,\ \Sigma_s' = C(\pi/180)\lambda q(\alpha - \beta)(1 + \lambda q)\ \{\ m - k_x(\pi/180)\lambda q\ \}\ /$$
$$m\ \{\ (1 + \lambda q)^2 + (\pi/180)^2\lambda^2 q^2(\alpha - \beta)^2\ \}$$

in terms of λq to the same order of approximation. And

$$\therefore\ \Sigma_s' = mC\theta\,(Nb/x)(\alpha - \beta)\ \{\ 1 + (180/\pi)\, m\theta\,(Nb/x)\ \}\ \{\ 1 - k_x\theta\,(Nb/x)\ \}\ /$$
$$[\ \{\ 1 + (180/\pi)\, m\theta\,(Nb/x)\ \}^2 + (\alpha - \beta)^2\, m^2\theta^2\,(Nb/x)^2]$$

in terms of the radius x and the unknown quantity θ.

Now compare this result with the formula for $\delta T/\delta x$; and notice that, since the terms in the denominators involving $(\alpha - \beta)^2$ are very small in practically every case, we can neglect them in both formulæ for a first approximation in finding a tentative value for θ. Then approximately :—

$$\Sigma_s' = mC\theta\,(Nb/x)(\alpha - \beta)\ \{\ 1 - k_x\theta\,(Nb/x)\ \}\ /\ \{\ 1 + (180/\pi)\, m\theta\,(Nb/x)\ \}$$

And similarly for $\delta T/\delta x$ approximately :—

$$\delta T/\delta x = C^2\rho b m(\alpha - \beta)\ \{\ 1 - 3\theta k_x\,(Nb/x)\ \}\ /\ \{\ 1 + \theta(180/\pi)\, m\,(Nb/x)\ \}$$

Now since

$$mC(\alpha - \beta)/\ \{\ 1 + \theta(180/\pi)\, m\,(Nb/x)\ \}$$
$$= \Sigma_s'/\theta\,(Nb/x)\ \{\ 1 - k_x\theta\,(Nb/x)\ \}$$
$$\therefore\ \delta T/\delta x = C\rho b\ \{\ 1 - 3\theta k_x\,(Nb/x)\ \}\ \Sigma_s'/\ \{\ \theta\,(Nb/x)\ [1 - k_x\theta\,(Nb/x)]\ \}$$

in terms of Σ_s'.

Hence, if we have any experimental fan which has a constant value of Σ_s' for all radii x we can employ the above formula to find the thrust of the fan, and conversely, if we know the thrust of the fan and the value of Σ_s' we can determine the value of θ. Further, it is evident that for all "good" angles of incidence α_r, $\tan\gamma$ is small compared to unity and $\tan\gamma \tan(\alpha - \alpha_r)$ is very small

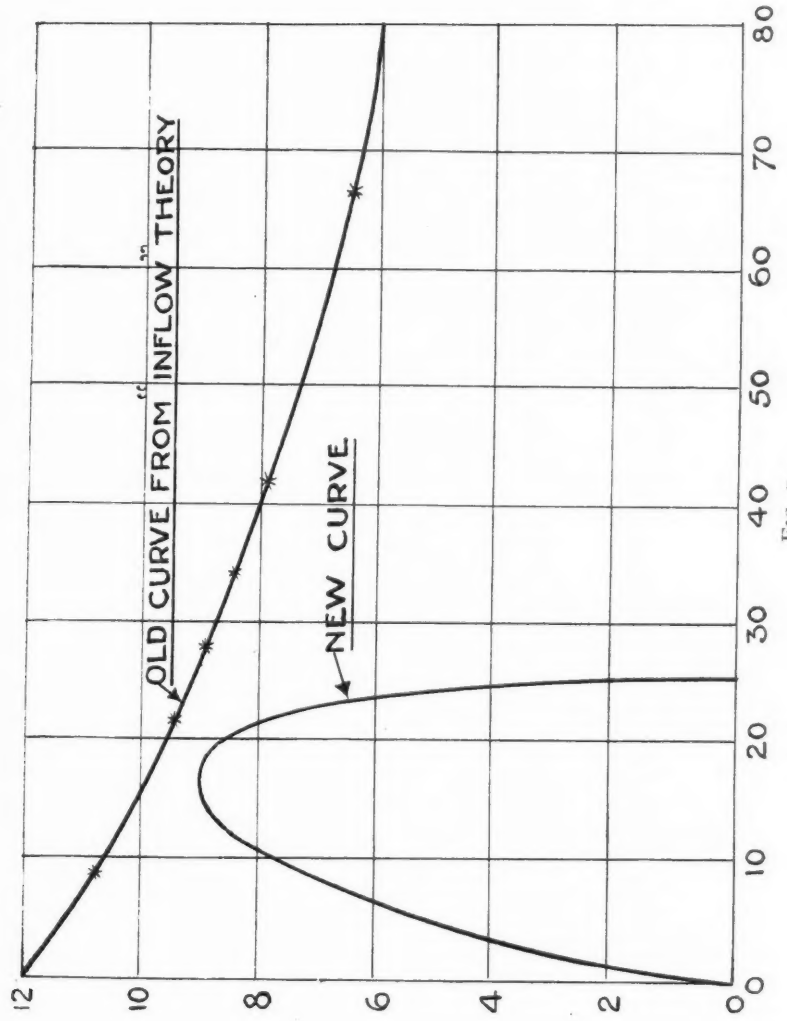

OLD CURVE FROM "INFLOW" THEORY
NEW CURVE
0
2
4
6
8
10
12
0
10
20
30
40
50
60
70
80

FIG. 7.

except quite near the boss where the thrust is vanishingly small, so that a further approximation gives:—

$$\delta T / \delta x = C\rho b \Sigma_s' / \theta \, (Nb/x),$$

and $\therefore$

$$\theta = \rho \Sigma_s' / T \int bC dx / (Nb/x)$$

from which the value of θ is at once found. Some years ago I made and tested two wooden fans, both of which were geometrically identical and of equal diameter. The diameter was three feet. One was a two-bladed and the other a four-bladed fan. They both gave identical results on test as near as I was able to measure at the time. In each fan the product (chord blade width × number of blades) was the same and equal to 4/3 feet, so that the four-bladed fan had blades one-half the chord width of the other. The chord blade width was constant along the blade length. The r.p.m. was in each case 1,050, the power being supplied by an electric motor of 0.6 b.h.p. rating running at 1,400 r.p.m., the reduction to the fan being by a flat belt drive of 3 : 4 reduction. The axial thrust recorded was a trifle over 12lbs., and the speed of in-draught normal to the screw disc was found by an anemometer to be approximately constant with blade radius and equal to about 16 feet per second.* The speed of out-draught was measured as about double this figure. From these admittedly rather rough test results I propose now to calculate the value of θ as a first tentative estimate.

$$\theta = \rho \Sigma_s' / T \int bC dx / (Nb/x)$$

$T = 12$lbs. / N = thrust per blade.

$$= (.00237 \times 16 \times 2\pi \times 17\tfrac{1}{2}) / (12) \int_0^{3/2} x^2 dx$$

$$= (.00237 \times 16 \times 2\pi \times 17\tfrac{1}{2} \times 27) / (12 \times 3 \times 8) = .391.$$

Hence, $\theta = .391$ as a first rough estimate.

Conclusions.

The theory enunciated above has been developed in order to, if possible, take the place of the "inflow" theory of the airscrew, which latter is too empirical, although the present paper is concerned only with the special case of the propeller working at a fixed point, without axial motion, after the manner of a fan. The theory given here is based upon blade interference and nothing else, and is amalgamated with and forms a correction upon the original "blade element" theory of Drzewiecki. It requires further development so as to include the general case of propeller action, but it is thought that the present paper will have achieved its main object if it draws attention to the fact that the "inflow" theory being admitted to be of too highly empirical a nature, a theory can be evolved which shall possess the same power in application as this older theory and which, at the same time, shall rest upon a more rational basis. The key and corner stone of the new theory is blade interference, the regime of which has only recently begun to be understood in its relation to all screw propeller action. Not only does this new theory not require the assumption—upon which the "inflow" theory depends—that the inflow/slip ratio is a constant, but it shows that this ratio varies and how it varies, the form of which variation is confirmed by experiment.

* Or slightly greater. It is here assumed that this figure is approximately equal to the normal inflow speed component.

APPENDIX.

From the two equations, when Σ_s' is a constant with radius:—

$$\delta T/\delta x = (C\rho b\Sigma_s')/\theta\,(Nb/x),$$

and

$$\delta Q/\delta x = \rho b\,[C^2k_x + (\Sigma_s')^2/\theta\,(Nb/x)],$$

we can determine the thrust T in terms of the power H and propeller diameter D. Assume constant blade width b. Then:—

$$NT = 2\pi n\rho\Sigma_s'/\theta\int_0^{D/2} x^2dx = (2\pi n\rho\Sigma_s'/3\theta)\,(D^3/8)$$

$$NT = (\pi n\rho\Sigma_s'D^3)/(12\theta) = \text{total axial thrust of propeller.}$$

And

$$N\,(\delta Q/\delta x)\,x = \rho NbC^2k_xx + (\rho\Sigma_s'^2x^2)/\theta$$

$$NH = 2\pi nN/550\int(\delta Q/\delta x)\,xdx = 2\pi n\rho/550\int[NbC^2xk_x + (\Sigma_s'^2x^2)/\theta]\,dx$$

$$= 2\pi n\rho/550\,[Nbk_x4\pi^2n^2\int_0^{D/2} x^3dx + (\Sigma_s'^2/\theta)\int_0^{D/2} x^2dx]$$

$$= 2\pi n\rho/550\,[(Nbk_x\pi^2n^2)\,(D^4/16) + (\Sigma_s'^2/3\theta)\,(D^3/8)]$$

$$= 2\pi n\rho/550\,[(Nbk_x\pi^2n^2D^4/16) + 6\theta\,(NT)^2/\pi^2n^2\rho^2D^3]$$

and

$$\therefore\ 6\theta\,(NT)^2/\pi^2n^2\rho^2D^3 = 550\,(NH)/2\pi n\rho - Nbk_x\pi^2n^2D^4/16$$

and

$$\therefore\ (NT)^2 = \{\,(550\,(NH)/2\pi n\rho) - (Nbk_x\pi^2n^2D^4/16)\,\}\,(\pi^2n^2\rho^2D^3/6\theta)$$

This gives the axial thrust of any fan, of constant chord blade width and constant normal component of inflow speed, in terms of blade width.

Suppose we put $Nb = \phi D$, so that the total blade width becomes a fraction (ϕ) of the propeller diameter D. Then we get, writing W for the total axial thrust (NT) and H for the total BHP instead of NH.

$$W = \{\,\pi^{\frac{1}{2}}n^{\frac{1}{2}}\rho^{\frac{1}{2}}D^{3/2}\sqrt{550}\,H^{\frac{1}{2}}/\sqrt{12\theta}\,\}\,\sqrt{\{\,1 - (\phi k_x\pi^3n^3D^5\rho)/8.550\,H\,\}}$$

Now I have previously shown elsewhere* that the thrust of any fan or helicopter can be represented by:—

$$W = \rho^{\frac{1}{3}}H^{\frac{2}{3}}D^{\frac{2}{3}}f(nD^{5/3}\rho^{\frac{1}{3}}/H^{\frac{1}{3}})$$

So that by equating these two equations we can find the form of the unknown function f. This gives:—

$$f\,(nD^{5/3}\rho^{\frac{1}{3}}/H^{\frac{1}{3}}) = (550\,\pi/12\,\theta)^{\frac{1}{2}}\,(nD^{5/3}\rho^{\frac{1}{3}}/H^{\frac{1}{3}})^{\frac{1}{2}}\,\{\,1 - (\phi k_x\pi^3/4.400)\,\,(nD^{5/3}\rho^{\frac{1}{3}}/H^{\frac{1}{3}})^3\,\}^{\frac{1}{4}}$$

So that, writing ψ for the argument $(nD^{5/3}\rho^{\frac{1}{3}}/H^{\frac{1}{3}})$, we get:—

$$f\,(\psi) = (550\,\pi/12\,\theta)^{\frac{1}{2}}\,\psi^{\frac{1}{2}}\,\{\,1 - \phi k_x\pi^3\psi^3/4.400\,\}^{\frac{1}{4}}$$

And the form of the function $f\,(\psi)$ is hence determinate and both ψ and $f\,(\psi)$ are non-dimensional.

Now I have shown elsewhere that if we take

$$F\,(\psi) = \rho^{\frac{1}{3}}f\,(\psi)$$

so that

$$W = H^{\frac{2}{3}}D^{\frac{2}{3}}F\,(\psi)$$

the value of $F\,(\psi)$ is round about 8 for many cases.

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* "The Helicopter Flying Machine," *Aircraft Engineering.*

Now in this new theory we find that the corresponding value of $F(\psi)$ is given by:—

$$F(\psi) = \rho^{\frac{1}{2}} (550\pi/12\theta)^{\frac{1}{2}} \psi^{\frac{1}{2}} \{ 1 - \phi k_x \pi^3 \psi^3 / 4400 \}^{\frac{1}{2}}$$

where the value of ρ is the "ground level" value of .00237, and $\rho^{\frac{1}{2}} = 1/7.5 = 2/15$, so that

$$F(\psi) = (2/15)(550\pi/12 \times 391)\psi^{\frac{1}{2}} \{ 1 - \phi k_x \pi^3 \psi^3 / 4400 \}^{\frac{1}{2}}$$

with $\theta = .391$ as found already. Then

$$F(\psi) = 2.56\,\psi^{\frac{1}{2}} \{ 1 - \phi k_x \pi^3 \psi^3 / 4400 \}^{\frac{1}{2}}$$

Now in order to get an idea of the order of values let us take some rough values for ϕk_x. Let $k_x = 1/60$, $\phi = \frac{1}{2}$ (not too large for a fan or helicopter), so that

$$\phi k_x \pi^3 / 4400 = 31/(2 \times 60 \times 4400) = 1/17{,}000$$

Hence,

$$F(\psi) = 2.56\,\psi^{\frac{1}{2}} (1 - \psi^3/17{,}000)^{\frac{1}{2}}$$

showing that for small values of ψ the last term in the equation is only a small correction, but for values of ψ of 20 and over the correction is very material.

We can now form the following characteristic table of values:—

ψ	0	5	10	15	20	25·7
$F(\psi)$	0	5·7	7·83	8·87	8·35	0

This is plotted in Fig. 7, together with the curve obtained from the "inflow" theory and published by me in "The Helicopter Flying Machine" (*Aircraft Engineering*, June, 1920, Fig. 5). It will be seen that although the two curves are so dissimilar in form the values of $F(\psi)$ are of the same order in the two curves in the "useful" region from $\psi = 10$ to $\psi = 20$, and that in this region the value of $F(\psi)$ is round about 8, as mentioned in the article referred to above. Thus, the new theory of blade interference is seen to give results of the right order in this case also.

REVIEW.

Automobile and Aircraft Engines in Theory and Experiment. Arthur W. Judge, A.R.C.S., London. Sir Isaac Pitman and Sons, Ltd.

This revised and enlarged edition of "High Speed Internal Combustion Engines" will be welcomed by all who are interested in theoretical and experimental work relating to automobile and aircraft engines, since the title truly describes the subject matter, and this is set out very clearly by a writer who is technically sound.

There are thirteen chapters, three appendices and a good index, comprising in all some 640 pages. The first chapter deals with combustion and explosion, and this is followed by an exposition of the thermodynamics of internal combustion engines which includes treatment of variable specific heat and entropy. Next, the real conditions obtaining in engines are compared with those assumed for the purpose of theoretical treatment, and this leads to a comparison of real and ideal thermal efficiencies.

Conduction, radiation, and cooling effects are then considered, after which the measurement of temperature, pressure, volumetric efficiency and power is dealt with at length. Then follows a chapter on altitude effects and supercharging, this portion relating chiefly to aircraft engines, and the mechanics of high-speed engines are then outlined. The last chapter but one is devoted to balancing, and the final chapter to the subject of fuels for automobile and aircraft engines. In Appendix II. the Still engine is described. Appendix III. comprises a table of aircraft engine particulars.

A satisfactory feature of the book is that it contains numerous references to important papers, etc., dealing with particular pieces of research. These references have been brought well up to the beginning of 1921.

The book was, however, issued too soon for reference to be made to the exceedingly valuable articles contributed to "The Automobile Engineer" by Ricardo entitled "The Influence of Various Fuels on the Performance of Internal Combustion Engines," and by Tizard and Pye entitled "The Character of Various Fuels for Internal Combustion Engines." A study of these matters is not now complete without a perusal of the articles referred to, or of the paper read by Tizard in May, 1921, before the North-East Coast Institution of Engineers and Shipbuilders entitled "The Causes of Detonation in Internal Combustion Engines," and on this account they are mentioned here.

Many important and helpful papers in transactions and journals are practically buried until they are epitomised in a book of this kind, and in co-ordinating and summarising the results obtained by various experimenters in this field, Mr. Judge has accomplished a very useful piece of work. Although some of the experiments quoted date back a number of years and were made upon engines which by modern standards were inefficient, they serve to illustrate points of fundamental interest, and their mention is justified on this account.

Messrs. Pitman are to be congratulated on the excellent printing of the text and the clearness of the many graphs, etc.

B. C. C.

PUBLICATIONS.

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